Temperature and Physical Modelling Studies of Open Windrow Composting

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Director of Studies

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ABSTRACT

There is a growing demand for sustainable forms of waste management due to both legislative pressures (e.g. the European Union Landfill Directive (99/31/EC)) and increasing public awareness of environmental issues. Composting of biodegradable waste materials to produce a stabilized beneficial multi-functional product (compost) is being widely promoted. Currently, the most popular method of composting is the open windrow method, whereby the mixed and shredded feedstocks are arranged in long rows termed windrows and turned on a regular basis. During the process the waste material is subject to aerobic exothermic microbial decomposition. Commercial composting operations suffer from the problem that much of the processing is performed using empirical approaches. Improved understanding of the composting process based on scientific methodology is required to allow composting to develop its potential as an economic, safe and reliable method of sustainable waste management.

This study used a series of large scale windrow-based seasonal field trials employing urban green waste as a feedstock, to investigate in unprecedented detail the temperature trends and patterns of behaviour within such structures. In addition physical-chemical profiling was undertaken. It demonstrated that windrow temperature development is not uniform in either a spatial or temporal sense. Temperature variation is a key feature of composting. All regions of typical windrows exhibited thermophilic and mesophilic temperature zones throughout the composting process. There was little seasonal variation. Sustained high temperatures were most widespread in the core regions at a height of around 1m. Thus, these areas should not be favoured during temperature assessment to avoid bias results. It was demonstrated that current methods of temperature assessment are inadequate. It is suggested that greater numbers of data points are collected at varying positions and instead of simply calculating overall mean temperature that individual trends are plotted. The use of temperature frequency distribution histograms and cumulative temperature plots is additionally advised. Increased windspeed (greater than approximately 15MPH) was demonstrated to be a major factor preventing the development and sustaining of thermophilic temperatures within windrows. It is recommended that commercial composters routinely assess windspeed and direction. Changes in organic matter content, bulk density and pH provided an indication of the composting process in the long term but lacked the sensitivity of temperature measurement. Surveying using electronic tacheometry allowed changes in windrow shape and volume to be assessed.

The field trial data allowed a novel physical compost model to be developed, based upon open windrow composting of urban green waste. Existing models are based on in-vessel composting systems and are technically flawed in certain key aspects. The model successfully simulated the initial stages of windrow composting, which was proven by experimentation and comparison with field trial data. The use of low level internal feedstock heating was demonstrated to be a viable method of stimulating natural enhanced microbial activity. A non-insulated model windrow and the employment of an environmental simulation system allowed the natural relationship between windrow and external environment to be modelled. The importance of such a model to the compost scientist and waste manager is highlighted. The study showed that it is possible to successfully physically model the open windrow composting process.

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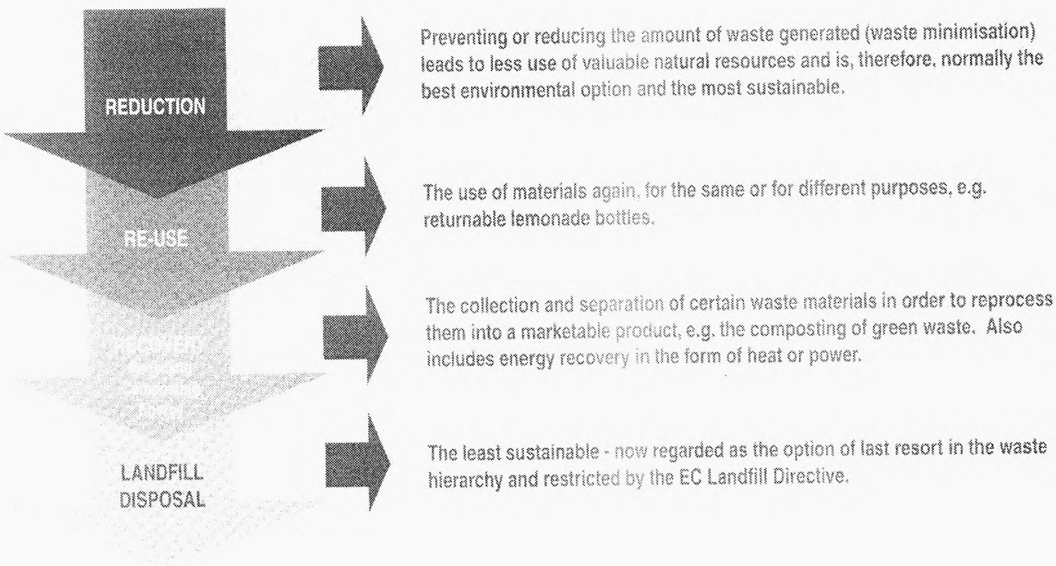
CHAPTER 1 – INTRODUCTION

Recent years have seen the greater adoption of pro-active environmental legislation at both national (United Kingdom) and international (European Union) level. This is due to the realisation that the environment is not an infinite resource, but a finite one with limitations that have become increasingly stretched in the modern industrial era.

THE WASTE MANAGEMENT HIERARCHY

The modern industrial era has seen the introduction of the concept of the "waste management hierarchy", which is a ranked scheme whereby more sustainable methods of integrated waste management are promoted (SEPA, 1999). The principle features of the hierarchy are outlined in Figure 1 (Fife Waste Strategy Area Group, 2001). Ideally there should be a reduction in the production of a waste and the use of raw materials. This is a long term objective of environmental policy. Ranked next in the hierarchy is the re-use of waste materials for either the same or a different purpose. This may range from the refilling of glass milk bottles to the reclamation of building and construction materials, i.e. wood, stone, brick and metal work. This is followed by the concept of recovery, reprocessing and recycling and includes the processes of composting, energy from waste systems (incineration to produce heat or electricity from waste), bioremediation (the use of microorganisms to "clean" wastes, especially soils) (Iwamoto & Nasu, 2001) and phytoremediation (the utilisation of green plants to remediate contaminated soil and water) (Garbisu & Alkorta, 2001). It also embraces the increasingly familiar technologies of aluminium and steel recycling as well as the reprocessing of waste paper, glass cullet and aggregates (Aberdeenshire Council, 2000; Anon, 2001). Finally, at the base of the hierarchy and least favourable, is disposal and this essentially comprises landfilling. The main purpose of much of the current legislation is to drive waste management practices away from simple disposal and toward increased sustainability and environmental responsibility.

Figure 1: The Waste Management Hierarchy Concept. This promotes more sustainable forms of waste management, which are represented at the upper levels of the hierarchy. Less environmentally friendly forms of waste management feature lower down (Fife Waste Strategy Area Group, 2001).



For example, in 1998, of wastes collected by Scottish local authorities, over 90% were landfilled (SEPA, 1999).

THE INTRODUCTION OF ENVIRONMENTAL LEGISLATION

The Landfill Tax

In order to meet the demands of a sustainable waste management ideology the last decade has seen the introduction of several pieces of environmental legislation, including the Environment Act 1995 and the UK Landfill Tax, initiated in 1996, which imposes a levy on the disposal of wastes to landfill. Current values (2001-2002) are £12 per tonne for active wastes and £2 per tonne for inert wastes. The rate for active wastes is set to rise by a £1 each year until 2004. The Landfill Tax is aimed at reducing the levels of materials entering landfills and encouraging the re-use and recycling of wastes. This reflects the *"polluter pays"* principle of modern waste management. Facilities exist within the legislation to allow waste handlers to be exempt from paying the tax if material is subject to reprocessing and recycling activities within a 12 month period. A system of Landfill Tax Credits also operates to allow waste management organisations to contribute to specified environmental research or improvement schemes and claim tax-refunds in return and is administered by Entrust (HM Customs & Excise, 2000).

The European Urban Wastewater Treatment Directive

The introduction of the European Urban Wastewater Treatment Directive (91/271/EEC) in the latter half of the 1990's has forced the water authorities (in Scotland) and companies (rest of UK) to develop more environmentally responsible methods for the handling and treatment of sewage wastes. It has resulted in a move away from minimum treatment and simple disposal to a more integrated system of waste management, which is designed to enhance the environment. The increased level of treatment required and the reduction in the routes of dispatch under the legalisation have placed both economic and technical burdens on the organisations (Davis, 1996; Barrett *et al*, 1995). The level of dewatered sewage sludge (biosolids; the solids material derived after partial treatment of sewage flows; McDougall, 1997) production has dramatically increased, especially in Scotland where most sewage (74%) was disposed of directly into the sea with minimum treatment prior to the 1998 ban (SEPA, 2001). This has resulted in the development of novel methods of reprocessing to derive new marketable products from this waste product. Examples include composting, alkaline stabilisation and dry pellets (Aitken, 1995; McDougall, 1997; Irvine, 1999). This approach both enhances the environment, by reducing marine pollution, and also by providing valuable new agronomic products rich in organic matter and nutrients that are often severely depleted due to modern farming practices (National Research Council, 1996; Irvine, 1999).

The European Union Landfill Directive

The European Union Landfill Directive (99/31/EC) is aimed at reducing the dependence most European states have on landfilling as a method of dealing with waste products. This is to be achieved by the banning of certain products such as liquids (2001) and tyres (2003) and the phased reduction of others (biodegradable municipal waste (BMW)) (SEPA, 1999; Burnley, 2001). Landfilling is now seen as the method of last resort and features at the bottom of the waste management hierarchy as an unsustainable and *"non-environmentally friendly"* waste management technique. The most important and demanding of these targets is the reduction and phasing out of biodegradable municipal waste from landfills. Biodegradable waste has been defined within the legalisation as waste that is capable of undergoing anaerobic or aerobic decomposition and typically within landfills produces leachates and landfill gas (methane) both which have a highly negative environmental impact and are major reasons for the existence of the Directive (Price, 2001). BMW can be envisaged (in the UK) as the paper, card, food, gardening, textile and related wastes generated by domestic and limited commercial activities which are collected and controlled by the local authorities (Price, 2001). Currently the UK landfills 85% of its municipal solid waste (all forms of waste from the above sources) and it is estimated that around 60% of this total is biodegradable (Price, 2001).

Phased Reduction Targets for BMW

The phased reduction targets for BMW within the Landfill Directive are: to 75% of the level at 1995 by the year 2010, 50% of the amount produced in 1995 by 2013 and finally by the year 2020 only 35% of the 1995 levels will be permitted to be disposed of *via* landfill (Burley, 2001). Based on data for 1995 (Department of the Environment, Transport & the Regions, 1999) around 18 million tonnes of BMW were generated in the UK, estimated from a biodegradability level of 60%.

The Directive will undoubtedly place great pressure on the waste producers (i.e. the general public who will have to think about their lifestyles (how "*green*" they are)) and the managers, especially the local authorities, who will need to radically change their waste management methodologies and techniques to implement the targets of the legalisation (Department of the Environment, Transport & the Regions, 2000; Price, 2001).

THE NATIONAL WASTE STRATEGY

The response to the aforementioned and other related items of environmental legalisation has been the production of waste strategy plans, for Scotland (National Waste Strategy – Scotland), England and Wales (National Waste Strategy 2000) and Northern Ireland (Waste Management Strategy for Northern Ireland) (SEPA, 1999; Department of the Environment, Transport & the Regions, 2000; Department of the Environment, 2000). These provide a framework by which each of these regions of the UK can plan and implement a more sustainable and integrated system of waste management.

Area Waste Plans

Within the National Waste Strategy for Scotland for example, there is a requirement to produce a series of 11 Area Waste Plans (AWPs) which each cover a small number of local authority areas, termed Waste Strategy Areas (WSAs). These are currently being prepared by local councils, the Scottish Environment Protection Agency (SEPA), local enterprise companies, the waste industry and voluntary organisations. The AWPs are designed to provide detailed information about waste arisings and flows within each of the geographic regions and how sustainable methods of waste management (i.e. the environmental legalisation) can be implemented on a local scale, especially the targets set out in the Landfill Directive on BMW. During 2001 a series of public consultation papers were published, outlining the situation and potential options for future waste management in each of the areas (Argyll & Bute Waste Strategy Area Group, 2001; Fife Waste Strategy Area Group, 2001; Forth Valley Area Waste Group, 2001; Glasgow & Clyde Valley Waste Strategy Area Group, 2001; Highland Waste Strategy Group, 2001; Tayside Waste Strategy Group, 2001). These will be followed by draft area waste plans before adoption of finalised AWPs.

Composting a key feature of National Waste Strategy

A key feature common to all the potential options for future waste management outlined in the above documents is the development of composting technologies for the reprocessing of biodegradable wastes. This is of especial interest firstly, because composting currently plays only a minor role in Scotland's (and the UK's) waste management system (22500 tonnes were composted by Scottish local authorities in 1998; SEPA, 2001) and secondly, scientific knowledge and technical standards concerning composting are still relatively limited. This suggests that if composting is to successfully fulfil the role of the major biodegradable municipal waste reprocessing technique, then a sustained scientific effort is needed to provide the waste management industry with the technical information and process – product standards.

THE WASTE MANAGEMENT TECHNIQUE OF COMPOSTING

Composting is the semi-controlled aerobic exothermic microbiological degradation and stabilisation of biodegradable waste materials to form a richly organic beneficial multi-functional soil-like material termed compost (Irvine, 1999).

The History of Composting Technology

Although starting to enjoy a renaissance, composting has a long history, with examples found globally during all time periods. Evidence of composting can be found in several ancient texts and other historical documents (Catton, 1983; Haug, 1993; Day & Shaw, 2001). These range from biblical and classical sources to medieval manuscripts. It may be reasonable to view the middens and cesspits beloved of archaeologists as more than simply ancient landfills and rubbish dumps, but also potentially as forms of simple composting systems, whereby given time, a source of rich organic manure–soil improver could be derived (Needham & Spence, 1997; Simpson *et al*, 1999).

Composting Virtually Forgotten in the West

China and other parts of Asia have a long tradition of using composting techniques to recycle agricultural wastes into valuable crop improvement products (Lopez-Real, 1996; Stenbro-Olsen, 1998). However in the West, much of this technology has been forgotten until recent years. There is of course the tradition of gardeners of both large and small plots, of the gathering together of clippings and prunings and placing them on the compost heap at the bottom of the garden, but this is small scale and practised as an art form rather than one with a scientific underpinning. Similarly, many farmers still have a "*dung heap*" in a corner of a field where the used bedding, animal faeces and waste feedstuffs from livestock is dumped. This may sit for years, undergoing slow degradation before application to the farmer's fields for soil improvement purposes. It is essentially a style of composting termed static pile composting.

MODERN COMPOSTING DEVELOPMENT

It is however only in the 20th century that both research into the process of composting and the product compost and application of the technique as a waste management system can be identified.

The Indore Process

A major milestone in the development of modern composting technology was the pioneering work of Sir Albert Howard in the 1920s and 30s at the Indore Institute of Plant Industry in India. Howard was one of the first to apply scientific principles to the understanding of composting (Haug, 1993). The work featured investigation into feedstock management, i.e. what and how much went into a system and also where and for how long. This led to the development of a "recipe" which resulted in a system called the Indore Process that is still a highly successful and widely practised form of composting, especially in many rural parts of the developing world. The basic process is outlined below (Howard, 1935):

1. Place a layer of brush on the ground to provide a base for the heap.
2. Build the pile in layers, first using a 6 inch layer of "green matter", like crop wastes or leaves. Next, add a 2 inch of manure, which in turn is covered by a light layer of topsoil and limestone (note the 3:1 volume ratio of green waste to manure).
3. Repeat the layering until the pile reaches a height of about 5 feet. Turn the pile at about 6 week intervals for about 3 months.

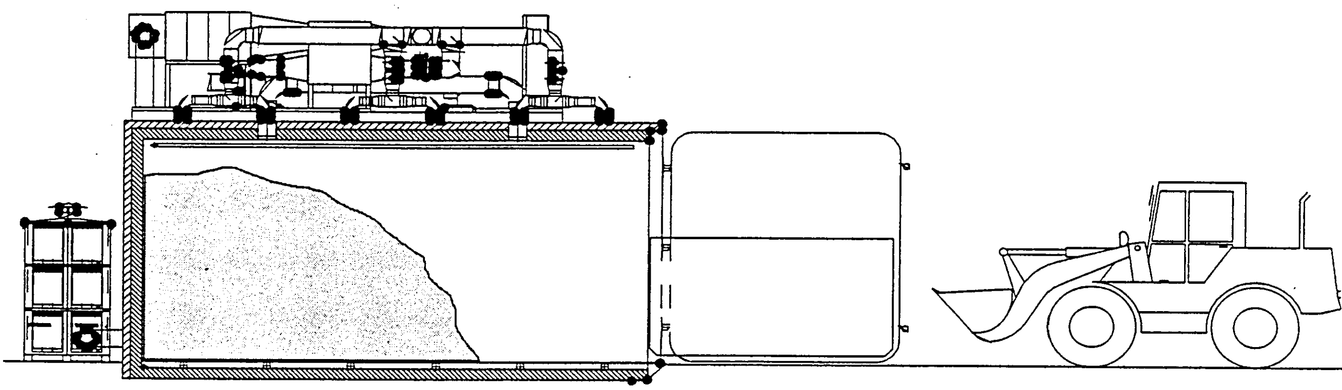
The importance of this method was that it was reliable and predictable. It allowed agriculturists to dispose of large volumes of crop wastes in an efficient, safe and hygienic manner, an important factor in topical regions of the world where uncontrolled putrefaction is rapid and presents health risks. Additionally, the resultant compost provided a soil improvement agent. The other point of note in this research, is that it demonstrates an early modern example of sustainable waste management. The production of large amounts of crop wastes resulted in the requirement for a reliable, rapid and safe method of dealing with it. This led to the application of scientific understanding to the traditional system of composting and resulted in the "Indore Process" and the production of valuable compost, which can be used in additional crop production.

Post-war Composting Technology Development

The 1940s–1960s saw further examples of composting research. Some of this research widened the selection of material used in composting away from simply agricultural wastes to include municipal solid wastes (MSW) and biosolids (Haug, 1993; Golueke & Diaz, 1996). However, it must be stressed that the level of research was still relevantly limited. The post-war period (approximately the 1950s and 60s) especially saw the application of engineering technology in the development of "in-vessel" composting systems (Haug, 1993; Stenbro-Olsen, 1998), where the wastes are contained and processed in some form of mechanically operated vessel or box akin to a fermenter or bioreactor, rather than an open heap (Figure 2). Examples of centralised composting plants are recorded in both Europe and the USA, an early UK example being the installation of a DANO drum (a Danish commercial drum system) in Edinburgh in 1955 (McDougall, 1997). However, whilst some of this early modern composting activity was quite successful in dealing with waste materials and producing a marketable product, most operations closed down quite rapidly. This was due to three major reasons; firstly economic pressures, as other more established forms of waste management such as landfilling and dumping at sea were much cheaper; secondly, environmental pressures, as legalisation and regulation were less restrictive and thirdly, the understanding of the composting process was far more limited

Figure 2: Example of In-Vessel Composting System. The Herhof Rottebox, a German design widely used in Europe for green waste composting (Herhof-Umwelttechnik GmbH, undated).

Herhof-Composting Box



than today, resulting in production difficulties such as odour problems and therefore, poor quality composts (Haug, 1993). These factors combined to keep composting very much an alternative and non-standard form of waste management.

The Resurgence of Interest in the 1980s and 1990s

It was only in the 1980s and 1990s that composting, mainly in the form of open-air systems, started to gain a foothold in the waste management industry and serious research into the science of composting developed. This was mainly due to public environmental pressure, the raft of pro-active environmental legalisation outlined earlier, economic and cultural changes and finally the improving base of technical knowledge that resulted in the success of composting operations (Stenbro-Olsen, 1998). Annual US surveys demonstrated a steady rise in composting in the 1990s, with under 1000 composting sites in 1988 to over 3800 in 2001 (Goldstein & Madtes, 2001). A similar picture is observed in the UK, with an annual 25% increase in the number of composting sites since the mid-1990s (Slater *et al*, 2001).

COMPOSTING PROCESS BASICS

What can be Composted?

Composting is a method for the treatment of a large range of organic waste materials. These include agricultural and crop wastes, gardening and parks wastes, logging and timber by-products, biosolids, paper, manures, municipal solid wastes, food and food processing wastes (Haug, 1993) as well as contaminated wastes and soils (bioremediative composting) (Semple *et al*, 2001).

How can it be Composted?

There are two major types of composting system, the open or non-reactor and the closed, reactor system (Rynk & Richard, 2001). Open systems are the most widely used and generally considered to be "*low tech*" in approach and more economical to operate. The material to be composted is not contained within a structure and composting normally takes place out of doors. Alternatively, closed in-vessel systems employ some form of containment of the waste materials during the process and use more engineering technology. Therefore, they are often termed "*high tech*" composting systems. Consequently, they tend to be more expensive to operate than open systems. However, regardless of approach, a well-run facility of either type can produce a product of equal value and marketability.

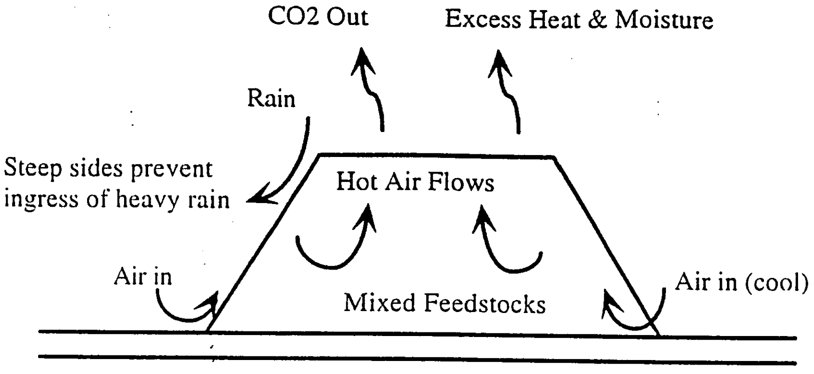
COMPOST WINDROWS

Windrows and static piles are the major examples of open non-reactor systems and represent the bulk of composting operations currently undertaken in the UK (Rynk & Richard, 2001). Windrows are extended elongated rows (heaps) of shredded and mixed waste (feedstocks) to be composted, which are regularly turned and reformed. They typically have a trapezoidal or pyramidal cross section and are approximately 2 to 7 metres wide at the base and 2 to 5 metres high and are of variable length (Stenbro-Olsen & Collier, 1994). Exact dimensions vary from site to site and will depend on the volume of material available, the equipment used to form the windrows, the size of the composting area and the preference of the composter (Rynk & Richard, 2001). Windrows represent the composting unit within which the degradative and stabilisation processes occur.

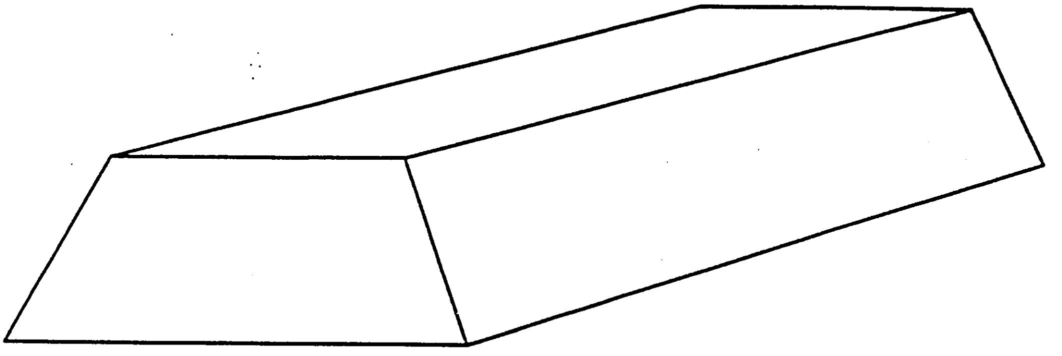
Windrow Structure

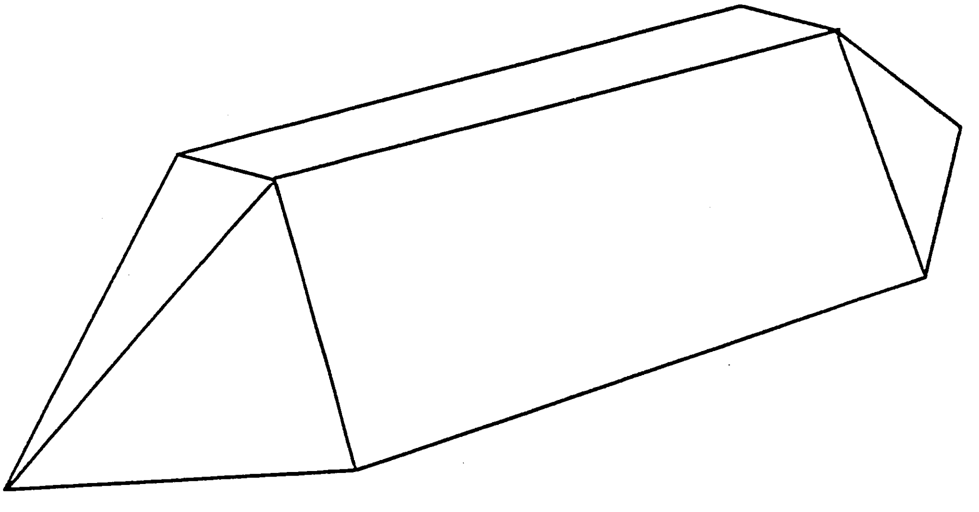
The structure of the windrow is important. Materials are typically shredded and mixed before being formed into the heap. This increases the surface area available and therefore,

Figure 3: The Basic Concepts of the Open Windrow Composting System. a) Cross-section of trapezoidal windrow, showing major features and movements of heat, gases and moisture. b) three-quarter view of typical trapezoidal windrow design. c) three-quarter view of typical pyramidal windrow design



A) Cross section of trapezoidal windrow


B) Trapezoidal windrow design


C) Pyramidal windrow design

the amount of material open to the actions of the microorganisms involved in this process. Relatively coarse shredding is preferred, as this produces a greater size range of particles and an open structure with good aeration properties, rather than chipping, which results in fine dense uniform particles (Stenbro-Olsen, 1998).

Feedstock Nutrient Balance

Mixing helps to ensure an optimum balance of nutrients, especially carbon, nitrogen and moisture. The balance of carbon to nitrogen is important, as these are the two primary nutrients required for the growth and reproduction of the microbial population. A starting value of around 25 to 30: 1 (C: N) is optimal, with values outside this range having a negative effect on the composting process. A lack of nitrogen will result in slow degradation and an excess leads to the production of ammonia. However, although a value around that quoted above is ideal, the calculation of biological available carbon and nitrogen is difficult and therefore, composters typically employ empirical methods to the balance of "greens" (N rich materials) and "browns" (C rich materials) (Iglesias-Jimenez & Perez-Garcia, 1991; Gartland *et al*, 1997; Stenbro-Olsen, 1998; Day & Shaw, 2001).

Moisture Requirement

Moisture content is important, as water is essential to the metabolic processes of the composting microorganisms (Collier *et al*, 1994). It also acts as an aqueous highway by which nutrients, organisms and heat can move. Therefore, excessively high or low levels of moisture are detrimental to composting. Optimal starting values are in the range of around 40% to 60%, with levels below that severally limiting microbial activity directly through lack of water and levels over that resulting in flooding of the pore space and restrictive gas exchange (Stentiford, 1996; Rynk & Richard, 2001; Day & Shaw, 2001).

Open Internal Structure Important

The internal structure of the windrow must be quite open in nature and retain a relatively high degree of porosity, rather like a system of internal scaffolding. This is essential for the success of an aerobic biological process, where the free movement of oxygen, moisture and carbon dioxide is essential (Collier *et al*, 1994). Compaction of the feedstocks, either because of their physical / bulk density (e.g. biosolids with their high moisture content and amorphous nature; Haug, 1993) or compressive forces due to the overall weight of the structure, reduces composting efficiently (Das & Keener, 1997; Joshua *et al*, 1998). This is due to the formation of anaerobic pockets and water-logging, which in turn impede the aerobic microbial process and drive the system towards a state of anaerobic degradation, which is typically slower, less efficient and produces a greater range of potentially toxic metabolic by-products than an aerobic state (Haug, 1993).

The typical shape of a windrow promotes the desired process. The steep sides help to prevent the ingress of excessive precipation and the structure allows the free movement of gases due to passive aeration (the chimney effect; Collier *et al*, 1994). In the case of biosolids composting this is aided by the addition of a dry bulking agent, such as wood or rubber chips, finished unscreened compost, straw or, in the case of co-composting operations, green wastes. These act to give the windrow structure and increased porosity as well as removing excess moisture (Irvine, 1999).

Windrow Turning

Windrows are generally turned by mechanical means on a regular basis. This is achieved by the use of either a front-end loader or a specialist windrow turning machine which can either straddle the structure or is pushed along the length of the windrow by a tractor. The level of turning varies from location to location with some employing several turns per week during the initial stages to more moderate levels of once a month or only once or twice a year. Much of this variation is due to the training, philosophy, economics, and level of equipment and type of feedstocks of the composting locale. Typically, windrow management systems are based on a pre-set interval of time, (e.g. once a month), or climatic patterns to reflect the moisture requirements of the windrows, or temperature changes within the structure, (e.g. when temperature falls by a particular amount or shows a downward trend for a number of days; Collier *et al*, 1994; Stenbro-Olsen & Collier 1994; Rynk & Richard, 2001).

Importance of Turning

Regardless of method or interval of turning, turning is important for two major reasons. Firstly, it helps to maintain optimum windrow structure and therefore efficient composting, by the continued reformation of good internal structure, (i.e. porosity, particularly in the early stages before the degradative process results in an noticeable increased bulk density of the materials) and the mixing of feedstocks to provide the microbes with renewed supplies of nutrients (Stenbro-Olsen, 1998). It is this that primarily allows the maintenance of good aeration and aerobic conditions and not the introduction of air during the physical turning of the windrow (Rynk & Richard, 2001). Secondly, turning increases the volume of material that is potentially exposed to the highest temperatures exhibited in the windrow and this ensures a good level of potential pathogen reduction within the composting waste (Stenbro-Olsen *et al*, 1995). This is especially important with high-risk wastes such as biosolids, but is important for all wastes as they naturally contain levels of animal and plant pathogens that are not acceptable in the finished product (deBertoldi, 1983; Collier *et al*, 1994).

THE MICROBIAL PROCESS OF COMPOSTING

Composting is an aerobic, exothermic microbiological process (Stenbro-Olsen, 1998). It can be divided into characteristic stages defined by the temperatures exhibited and the underlying types of microbe producing the heat (Catton, 1983; Haug, 1993; Day & Shaw, 2001). Figure 4 shows the major phases of a typical composting process.

Microbial Succession and Diversity

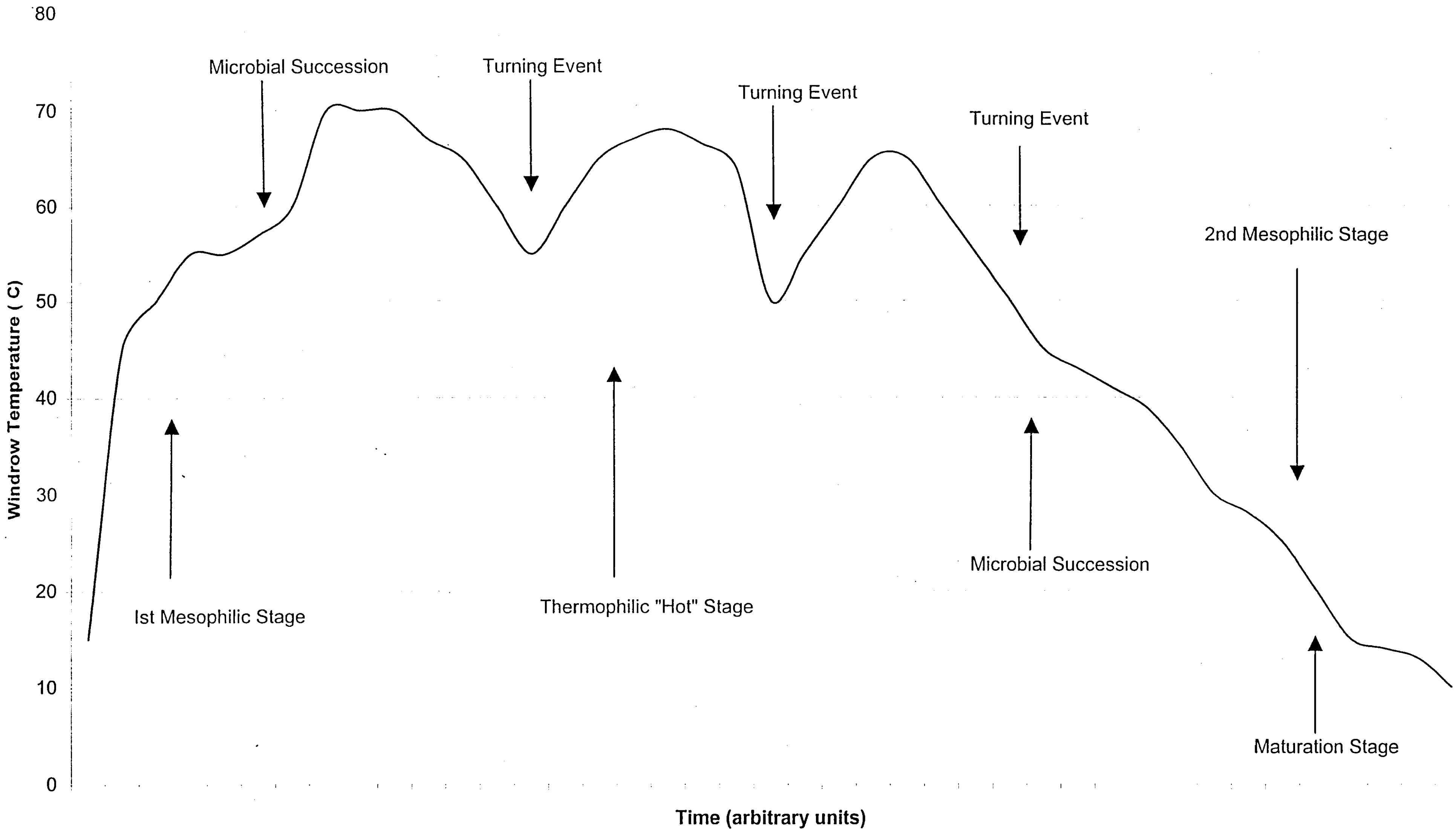
A feature of composting systems is the concept of microbial succession. This is a process whereby as different physical-chemical-ecological conditions develop and change within the windrow, different groups of microorganisms succeed each other as the major type of degradative organism present (Golueke, 1992; Collier *et al,* 1994; Stenbro-Olsen, 1998). This has been demonstrated both by classical microbiological techniques (Stenbro-Olsen, 1998) and also by molecular biology approaches (Blanc *et al*, 1999; Peters *et al*, 2000) The types of organisms are generally classified by their optimum growth range temperatures. Mesophiles are a group of microorganisms (bacteria, actinomyces, yeast, fungi) which grow optimally at between 25°C and 45°C. Thermophiles are microorganisms with a growth range of between 45°C and 80°C. Microbes from within these two types form the bulk of the organisms responsible for the degradation and stabilisation of the organic wastes in a composting operation (Day & Shaw, 2001) Table 1 shows the range of microorganisms identified by Stenbro-Olsen (1998) during composting experiments carried out using green waste derived windrows. Composting organisms have been isolated and characterised by microbiological techniques and by molecular probes (Stenbro-Olsen, 1998; Sakai *et al*, 1998; Chefetz *et al*, 1998; Beffa *et al*, 1996).

THE PHASES OF CLASSIC WINDROW COMPOSTING

The First Mesophilic Stage

When shredded waste is formed into a windrow, it has a large indigenous population of microorganisms. These are primarily mesophiles and are naturally associated with the

Figure 4: The generalised temperature trends observed in an idealised open windrow composting system over time, with major events indicated (Catton, 1983; Day & Shaw, 2001).



80
70
60
50
40
30
20
10
0
Windrow Temperature (C)
Microbial Succession
Turning Event
Turning Event
Turning Event
2nd Mesophilic Stage
Ist Mesophilic Stage
Thermophilic "Hot" Stage
Microbial Succession
Maturation Stage
Time (arbitrary units)

decay of organic material. Many are opportunistic plant pathogens, which under normal growing conditions would be kept in check by the plant's defence systems, but when the material is harvested this barrier is no longer in operation and the microorganisms can successfully attack the structure of the plant material (Collier *et al*, 1994).

Table 1. A List of Microorganisms Identified During Studies of Green Waste Derived Open Windrow Composting (Stenbro-Olsen, 1998)

Bacillus spp	*Penicillum* spp
B. stearothermophilus	Yeasts
B. subtilus	*Salmonella* spp
B. cereus (type 1)	*Vibrio* spp
B. macerans	*Pasteurella* spp
B. pumilus	*Erwinia* spp
B. lentus	*Serratia rubidea*
B. firmus	*Enterobacter* spp
B. megaterium	*Proteus* spp
Clostridium spp	*Aeromonas* spp
Escherichia spp	*Staphylococcus aureus*
Aspergillus fumigatus	*Pseudonocardia thermophila*
Neurospora crassa	*Mucor* spp

Heat Production

The mesophilic community present at the start of the composting process utilises the readily available supply of nutrients, such as the simple sugars, amino acids, small peptides and low molecular weight carbohydrates, to grow and reproduce rapidly (Stenbro-Olsen, 1998). This metabolic activity produces a large amount of heat as a waste product. This elevation in the temperature of the environment within the windrow structure further increases the metabolic rate of the organisms and hence their level of growth. The resultant heating effect found within the inner parts of the windrow is compounded by the insulative effects of the rest of the windrow structure, which traps the heat and retains it within the composting body. This leads to a continued increase in the temperature of the windrow. The windrow temperature indicates both the performance and stage of the composting process (Rynk & Richard, 2001). Therefore, temperature is an ideal means of process monitoring of commercial composting operations, which in theory is a simple operation able to be achieved by the use of a suitably encased temperature probe such as a thermocouple and trained non-specialist plant operatives. However, this is not the case, as although a generic pattern of temperature development within a windrow is known, the pattern of that heating, (i.e. temperature-time distribution profiles), is a complex issue which is currently little understood. The importance of these factors to the efficiency of a composting operation both in terms of degradation and stabilisation of waste materials and importantly their sanitisation is undervalued (Stenbro-Olsen *et al*, 1995; Fernandes & Sartaj, 1997; Joshua *et al,* 1998).

First Microbial Succession Occurs

When the temperature within a windrow approaches 45°C (which generally occurs within a day or two after establishment) the positive effect on the rate of growth of the initial mesophilic microorganisms is lost (due to thermally induced degeneration such as enzyme denaturation) and a decline in the numbers of viable mesophiles is observed. At this point the first of the microbial successions occurs, when the mesophilic community is succeeded by the thermophilic one, because the mesophiles are no longer capable of competing effectively with the emerging thermophiles. Stenbro-Olsen (1998) demonstrated that the change from mesophilic to thermophilic could be prolonged and "*unclean*" in nature with some mesophiles effectively out-competing the virgin thermophile community at temperatures of 45°C and above. However, other factors such as changes in the pH of the material due to the production of sugar acids and additional changes in the nutrient profile will also have an effect on the decline of the mesophilic community.

The Thermophilic Stage

At this point the windrow enters what is termed the thermophilic or hot stage of the composting process. Temperatures within the structure continue to rise as the metabolic activity of an expansive thermophilic community increase the temperatures to between 70°C and 80°C (Stenbro-Olsen, 1998). During this hot period, which may last several weeks or months depending of the nature of the feedstocks and the regularity of the turning regime, the bulk of the degradative activity occurs. Thermophilic microorganisms are capable of efficiently breaking down a wide range of different types of organic polymers (starches, lipids, cellulose, hemicellulose and lignin; Stenbro-Olsen, 1998). The rate of this breakdown is far faster, because of increased biochemical reactions, than that carried out by mesophiles in lower temperature environments and one of the reasons why thermophilic temperatures are encouraged within modern composting systems. The efficient breakdown of these materials is carried out by a range of different microorganisms, which not only comprise aerobic species, but also anaerobic and facultative anaerobic species as well (Rynk & Richard, 2001). Thus, it must be noted that although composting is primarily an aerobic process the presence of a certain amount of anaerobic activity is warranted if effective degradation of the waste is to be realised.

Optimal Temperatures

It is suggested that the greatest numbers of microorganisms and greatest species diversity occur within the temperature range of approximately 45°C to 60°C and therefore, the most effective breakdown of the waste (Rynk & Richard, 2001). Prolonged or widespread temperatures in the 65 and 70 degree zone are likely to reduce both the numbers and range of microorganisms actively decomposing the waste material. This is due to a process of microbial self-kill induced by the excessive temperatures resulting from rampant metabolism. However, work by Stenbro-Olsen (1998) showed that although the diversity of microbes present at higher temperatures was reduced, the overall numbers and activity of these organisms was not impaired and the efficiency of decomposition was not retarded.

Pathogen Reduction and the Importance of High Temperatures

The maintenance of temperatures within the thermophilic zone for extended periods is also important for the effective reduction in the number of potential pathogens (animal, plant and human) as well as weed seeds (Stenbro-Olsen *et al*, 1995). Interestingly, many of the microorganisms involved in the mesophilic degradation of the waste are classed as pathogens (Stenbro-Olsen, 1998). Table 2 shows a selection of some the temperature – time exposure guidelines for the reduction of potential pathogens in composting material. It is unclear from the sources (Strauch, 1996; Stentiford, 1996), but most of the regulations appear to refer mainly to biosolids composting. The European Union is proposing a pathogen reduction temperature system of either 55°C for two weeks with five turnings or 65°C for 1 week and two turning events within the "Biological Treatment of Biowaste" document (European Commission, 2001).

Lack of Standard Methods for Temperature Assessment

It is important to note that there is no clear guidance on how temperature measurements should be made, (i.e. how many points and where within the windrow). This is vital if a meaningful average windrow temperature is to be derived and the maximum amount of feedstocks exposed to the sanitising effects of the most active (hottest) parts of the windrow. The killing of microbes is not only a matter of reaching an "*inactivation temperature*", but is also critically linked to exposure time (Haug, 1993; Stenbro-Olsen, 1998). The pathogen containing waste must be held at the chosen inactivation temperature for sufficient time for there to be an effective level of pathogen destruction. Material that only achieves the critical temperature transitorily is unlikely to result in the reduction of potential pathogens to acceptable levels. Research by Stenbro-Olsen (1998) indicated that a windrow temperature of 55°C (a commonly quoted "*kill temperature*"; Table 2) for 48 hours did not eliminate mesophiles, but only suppressed their metabolism. There is a relationship between the inactivation temperature at the length of exposure time. The length of exposure time at a given temperature needed to reduce viable microorganism numbers by 90% is termed the D value or decimal reduction time (Atlas, 1995). The higher the temperature the shorter the exposure time required to achieve the same degree of microbial "*kill*". The effectiveness of temperature induced pathogen destruction is further complicated by the fact that the feedstocks are heterogeneous in nature and the physical–chemical conditions within the windrow are similarly not uniform. This suggests that temperature distribution is non-isothermal and that each of the feedstock constituents will have different heat retention characteristics, which will affect the ability of the windrow to efficiently kill pathogens.

Table 2. Examples of Temperature–Time Requirements for the Reduction of Potential Pathogens in Composting Wastes Materials in Various Countries (Strauch, 1996; Stentiford, 1996)

Country	**Temperature –Time Requirements**
Austria	>60-65°C for at least 6 days
Belgium	60°C for 4 days
Denmark	>55°C for at least 2 weeks
France	60°C for 4 days
Germany (open windrow)	>55°C for at least 2 weeks or 65°C for 1 week
Germany (closed system)	>60°C for at least 1 week
Italy	>65°C for 2-3 consecutive days (final material must be "biologically stable" to prevent regrowth
Netherlands	55°C for 2 days
Switzerland	>55°C for at least 3 weeks or >60°C for 1 week or a temperature / time combination of equal value
USA - Sewage Sludge Biosolids Processes to Significantly Reduce Pathogens	
(open windrow)	>40°C for at least 5 days or >55°C for 4 hours during the 5 days
USA – Sewage Sludge Biosolids Processes to Further Reduce Pathogens	
(open windrow)	>55°C for at least 15 days with at least 5 turnings
(closed system)	>55°C for at least 3 days

Windrow Maintenance

If a windrow is not maintained, (i.e. it is not regularly turned and reformed), then the thermophilic conditions exhibited during the hot phase will decline and as a result, the composting efficiency will also fall. Therefore, it is normal for windrows to be turned during the thermophilic phase to ensure that windrow structure is optimized and high temperature decomposition is prolonged for as long as the physical properties of the decomposing waste allow the proliferation of thermophilic microorganisms (Stenbro-Olsen *et al*, 1995).

Microbial Succession Event – Second Mesophilic Stage

Following this a point is achieved where, regardless of the level of turning and mixing of the feedstocks, the windrow is no longer able to maintain the high temperatures observed during the thermophilic phase and the average temperature begins to decline. At this point the next microbial succession event occurs, where there is a movement away from thermophiles predominating and a return to a mesophilic community (although not the same as during the primary mesophilic stage). This change is due to the changing physical and chemical properties of the windrow. After a prolonged period of activity the thermophiles will have broken down and assimilated a large proportion of the available nutrient sources, leaving only the more recalcitrant and difficult to decompose materials, such as the lignin in woody wastes. These nutrient sources are less available to thermophilic organisms and therefore, allow mesophiles to compete more effectively. However, Tuomela *et al* (2000) suggested that lignin can be broken down during both the thermophilic and secondary mesophilic stages depending on the microbes present, the temperature exhibited and the level of lignin in the feedstocks. The production of metabolic by-products, changes in pH, moisture content, conductivity, porosity and bulk density will also combine to make the microbial environment less suited to a thermophilic community and more adapted to a mesophilic one (Day & Shaw, 2001).

Maturation Phase

The windrow then enters the maturing and curing phase of composting. It is a very important part of the compost making process, as this represents the major stabilization period. Continued decomposition of the remaining nutrients occurs, but as the overall level of microbial metabolic activity is much lower, less heat is generated and temperatures tend to slowly return to near ambient. The increased bulk density (due to decomposition) of the material by this stage also means an increase in the heat energy (derived by microbial activity) needed to raise the temperature to a given level. There is a linear relationship between heat generation and bulk density (Stenbro-Olsen, 1998). However, in large windrows temperatures may be retained in the 30°C to 40°C range for extended time periods (Haug, 1993). This is due to the insulating effects of the large masses present. Turning may be used to release this trapped heat, but can be counter-productive by increasing the rate of aeration and allowing reinfection by opportunistic pathogens.

Development of Beneficial Compost Characteristics

The lower temperature microorganisms present at this stage are important not only for breaking down of the remaining available nutrients, but also for the maturing of the "*green*" compost. They are able to metabolise a range of metabolic by-products left by the thermophilic community, many which are phytotoxic (harmful to plants) (Shiraupour *et al*, 1997; Bess, 1999). Interestingly Ozores-Hampton *et al* (1999) suggested the use of immature MSW-biosolids composts as natural weedkillers because of their phytotoxic effects when used in the furrows between crop plants. Additionally the final bioconversion of carbon and nitrogen species occurs, resulting in the formation of plant available nutrient forms in the compost material (Pare *et al*, 1997; Garcia *et al*, 1991).

Plant Disease Suppression

The microorganisms present at this stage are responsible for the various beneficial characteristics reported when using composts, concerning plant disease suppression and improved plant growth (Boulter *et al*, 2000; Brinton *et al*, 1996). Firstly, the thermophilic conditions during the early stages reduce plant pathogen levels. Secondly, the mesophilic community within the compost is believed to out-compete potential plant pathogens for space and nutrients. Thirdly, the activities of antibiotic production, induced resistance against pathogens and spore germination inhibition are known to occur within the mesophilic community within the compost. Successful protection against a range of root rot and wilt type diseases in a range of plant species has been reported. These include the control of club root, white rot, brown rot as well as diseases caused by *Phytophthora* and *Fusarium* (Gouin, 1995; Hedges, 1996; Dickerson, 1996; Craft & Nelson, 1996; Boulter *et al*, 2000). Kannangara *et al* (2000), found that composts produced *via* thermophilic windrow based composting were able better to suppress *Fusarium* rot than growth media produced by vermicomposting (worm based mesophilic composting) or anaerobic digestion. The beneficial effects resulting from these microorganisms seem to be enhanced with increased maturation of the compost (Bess, 1999). This may be coupled to the level of stabilization of the compost, (i.e. the structural characteristics of the material), the level of mineralization of the organic matter and the form of the nutrients most useful to successful plant growth and development.

COMPOSTING MODELS

Improved composting could come about through the development of compost models, both mathematical / computer based theoretical examples and physical small-scale systems operational in the laboratory environment.

The Potential Benefits of Composting Models

The development of model systems potentially allows the researcher to gain new insights into the composting process, which being a dynamic multifaceted process is not easily understood or possible to observe, particularly in the field. This is due to the large range of factors which could be affecting the microbial reactions within all or part of the windrow throughout all or part of the compost production cycle (Hogan *et al*, 1989; Kaiser, 1996). Additionally, models can be used to identify potential problems or shortcomings in process or operational methodology. The discovery that a particular waste mix or turning regime may not reliably allow the development and prolongation of thermal microbial inactivation temperatures, highlights the potential value of good quality compost models. This could be used to develop realistic and achievable process standards and final product quality assurance. The lack of such standards and the ability of compost producers to attain such reference points is often quoted as a reason for not employing or accepting composting as a sustainable waste management technology, especially in the UK (Composting Association, undated; Gilbert & Slater, 2000; Slater *et al*, 2001).

Predictive Models

Another use of compost models is their use as predictive indicators to measure the success of composting certain wastes. Of particular interest are "*non-standard*" feedstocks such as contaminated organic wastes from an industrial process or environmental situation or the contaminated soils from the numerous brownfield sites which litter the post industrial landscape of the UK and many other nations which have seen the decline in the old heavy industries in the post-war period. The UK has over 300,000 hectares of contaminated land (Environment Agency, 2001; Scottish Executive, 2001). Composting in its role as a bioremedative treatment could assist in the clear up of such ground, along with other novel technologies like phytoremediation, but only if a comprehensive knowledge of the potential and limitations is gained. The benefits of knowing whether a waste material is suitable for composting and / or how effective a certain composting regime is at achieving a proscribed level of decontamination and treatment is clearly valuable.

MATHEMATICAL COMPOSTING MODELS

The Complexity of Modelling the Composting Process

Mathematical composting models attempt to better understand the processes involved by reducing everything down to a series of equations and mathematical statements. The success of such models is dependent upon the quality of the original raw data and its interpretation used to derive the final mathematical expressions of the biological activities within the composting system. This is a difficult task, particularly with composting, which is a complex microbiologically driven process, which dynamically interacts with its surroundings. This is further complicated by the fact that composting is not a single process, but a series of successional events each with different interactional possibilities. Finger *et al* (1976) used a heat and mass transfer model to describe the aerobic growth of microbes within compost. This may be developed further in that different composting methods, (e.g. windrows, static piles and in vessel systems), are unlikely to behave in a similar fashion, even if overall process reactions and eventual product are thought to be essentially the same in nature (Kaiser, 1996). Stombaugh and Nokes (1996) noted that although models had been designed to describe aerobic composting the underlying biological aspects of the process had been neglected.

Recent Examples of Mathematical Models

Nakasaki *et al* (1987) produced a theoretical model, which was designed to assess the optimum rate of aeration (for drying) and reaction temperature of a sewage sludge composting operation using a horizontal bin reactor. The mathematical model was field tested and found to be credible. Haug (1993) produced a range of mathematical process models, also investigating the composting of biosolids. These were designed to allow the simulation of the effects of thermodynamics and kinetic principles on the composting reaction. The composting simulation model developed by Stombaugh and Nokes (1996) featured a model based on microbiological growth kinetics (Monod kinetics) and the requirements for such biological activity within the environment of the composting vessel. Hseih et *al* (1997) developed a model for nonisothermal static composting (i.e. unturned systems) using heat and mass balance equations to present a dynamic model which aimed to show the temporal variations of the components within the system. Data from laboratory scale reactors composting vegetable waste in the subtropics was used to derive a model of the kinetic behaviour and operational parameters of thermophilic composting (Huang *et al,* 2000). Seki (2000) has promoted a stochastic model for batch type composting. In order to evaluate the value of process and stability indicators in biosolids composting Lasaridi *et al* (2000) developed a model describing the process rates in terms of respirometric and volatile solids data. Higgins and Walker (2001) published a model based on substrate specific kinetics and energy and mass transfer models to observe the process dynamics of the decomposition of synthetic food wastes, which was trialed against pilot scale experimental data.

Windrow Based Investigations

In general, published mathematical models for composting are primarily based on in-vessel composting systems, with little reference to the more popular windrow technique. The work of Robinzon *et al* (1999 & 2000) investigated the bulk parameters of the windrow based composting process and the energy and mass balances of windrow composting systems situated in Israel. Screened MSW and crushed garden waste were utilized after partial stabilization with a rotating drum vessel to form windrows which underwent different treatments and monitoring to derive and test modelling data.

The Practical Value of Mathematical Models

The requirement for a good mathematical composting model is clear. The provision of valuable data by such models concerning the theoretical behaviour of a given composting system and / or blend of feedstocks is undoubtably of assistance to the laboratory based compost scientist or process engineer allowing novel insights to be made. However, the practical in-field application and value of mathematical models must be questioned. It can be suggested that the average compost site manager and operative would find both the understanding of the logic of most models difficult to comprehend (models tend to designed by specialists for specialists) and they are looking for practical, field employable solutions to the potential problems that are encountered. However, mathematical models are useful because they potentially provide novel information about the process characteristics without the need to employ actual waste materials (saving space, money, time and potential environmental damage) and may allow the assessment of parameters which are difficult to achieve in pilot or field systems. However, although valuable, mathematical models are of rather limited practical use to the commercial composter who requires more direct robust answers related to popularly used methods of composting, such as open windrows, to the questions of operational and process efficiency.

PHYSICAL COMPOSTING MODELS

Physical composting models, where the rationale is to scale down and produce a small sized version of the composting system, allow the researcher to physically change composting conditions such as aeration, agitation or feedstock composition in real time and observe the changes that occur to some given parameter. Such models allow these operations to be carried out in the laboratory without the need to establish full size field trials utilizing large volumes of waste materials and allow the researcher to monitor the reaction or assess the resultant compost in detail (Hogan *et al*, 1989).

The Need for Physical Models

The need for such systems is two-fold. Firstly, they allow detailed investigation into the composting process, furthering the scientific knowledge of such microbially based bioreactions, which could result in improved efficiency in large-scale commercial composting operations. Secondly, they potentially let composters predict the outcome of composting, using a particular set of conditions or feedstocks, in a safe and economical manner. The establishment of full sized test windrows for example requires the procurement and processing of a large volume of potentially contaminated material (both in the sense of pathogenesis and levels of xenobiotics) by site personnel and machinery. Both operations raise safety considerations and involve the use of economic resources. Additionally, the time and area which is taken running a full sized trial may be extensive and could result in wasted time and space if the outcome of the trial is not successful. This may lead to costly alternative removal or treatments as required, which is an important consideration to a commercial composting site operator. Environmental impact is also reduced by the use of a small-scale laboratory based system. The detailed results and data possible from a physical model allows the researcher to gain information that is not easily practicable in a routine sense from full sized composting operations. The need to test novel mixes, feedstocks, or conditions is of growing interest to the waste management industry as composting becomes more important. A demand for greater efficiency, reliability and safety during the process and higher end-product quality, safety and marketability is a likely feature of the future composting industry as well as the regulatory authorities such as SEPA and the general public.

The success of a physical composting model design is, like that of a mathematical one, based on the quality of the data used to construct it and interpret the reactions visualized during a trial. This must be based on good field data and understanding of the composting process from use of the existing scientific knowledge base.

The Development of Physical Composting Models

Some of the earliest published examples of physical compost modelling are by Wiley (1956 & 1958), who carried out investigations into the high rate composting of garbage and refuse material. Other early work includes that of Schulze (1962), Jeris and Regan (1973a, b & c) and Suler and Finstein (1977).

As long ago as 1982, Ashbolt and Line (1982) classified laboratory scale systems into two styles, namely rotating drums and stationary cylinders. Review of available literature in the following twenty years, both the level of published material and the advancement in design has been limited largely retaining the position of Ashbolt and Line's classification (Sikora *et al*, 1983; Bach *et al*, 1984; Nakasaki *et al*, 1985; Hogan *et al*, 1989; Adenuga *et al*, 1992; Palmisano *et al,* 1993; Tseng *et al*, 1995; Gilmour *et al,* 1996; Stombaugh & Nokes, 1996; Kaiser, 1996; Papadimitriou & Balis, 1996; Baker *et al*, 1999; Bari *et al*, 2000a & b; Huang *et al*, 2000; Kim *et al*, 2000; Bari & Koenig, 2001).

Types of Physical Model

Physical composting models can be grouped into three main types. The first could be termed generic non-specific idealistic models, whereby, there is only a limited attempt at mimicking the behaviour of a specific composting system environment, (e.g. a windrow or aerated static pile). The main purpose of these models is essentially to model a generic composting type reaction or simply the decomposition (mineralization) of organic waste materials (Gilmour *et al*, 1996). This may be achieved with only minor reference to *in vivo* systems, which limits their value when considering the practical enhancement of composting operations and the development of a viable predictive model system.

Other published physical model systems attempt to model composting processes in a more specific manner, with greater emphasis on the reactions being driven by microbiological activity. There is more effort made to derive behaviour within the container that is in some way characteristic of that observed in actual composting systems (even if that is only for a generalized composting method, i.e. not specifically an aerated static pile or rotating drum for example) This second type can be viewed as general purpose compost models (Hogan *et al*, 1989; Tseng *et al*, 1995; Papadimitriou & Balis, 1996).

Thirdly, some models are essentially scaled down versions of particular in-vessel systems (pilot plants). These can provide the compost researcher with a great deal of information concerning the behaviour of the selected in-vessel system, which could enable improved composter design or provide valuable information on whether an potential operator should purchase and install that style of vessel (Nakasaki *et al*, 1987; Bari *et al,* 2000a & b; Bari & Koenig, 2001).

The Need For More Realistic Models

There is a need to develop models away from chemostat styled fermenters towards more specific representations of the microbial driven biochemical exothermic series of reactions, which are composting. The use of contained sealed vessels may allow the study of such effects as rate of forced aeration (Bari *et al,* 2000a & b), artificial heat input (Jeris and Regan, 1973a, b & c) or moisture addition (Baker *et al,* 1999) on the degradation of organic waste materials, and although this may go some way in modelling the reactions within a larger in vessel system or justifying a theoretical model (Stombaugh and Nokes, 1996) there is no indication that this represents the behaviour of a windrow exhibiting microbial heat production and natural aeration in the field. There is commonly a failure to link data obtained *via* a model to field derived data. Models seem to be developed in isolation from commercial composting systems especially windrows and, this must limit their value as practical predictive models. Existing physical models do not seem to consider both the importance of attempting to model the extremely popular open windrow composting system, and the design of model systems which reflect the behavioural characteristics that occur in production scale systems in the field. There is a tendency to induce the heating of the feedstocks within the test vessels to gain the exothermic degradation characteristics that are associated with composting, without reference to how and importantly where these elevated temperatures are produced and maintained within the structure in the field. Models commonly employ some form of external insulated jacket and heating system to induce and maintain thermophilic temperatures within the vessel. Research (Stenbro-Olsen *et al*, 1995; Stenbro-Olsen, 1998) has demonstrated that microbially generated heat is produced internally within the central regions of composting mass and radiates outwards. Heat is not produced at the outside of the windrow (i.e. the external environment) and transferred into the structure. Although there is logic to the provision of an insulated layer to combat rapid heat loss due to the small volume-to-surface area ratio exhibited in model systems and the possibility that such a layer could mimic the naturally insulating outer layers of a windrow, it could also be reasoned to be acting as an unnatural barrier to the transfer of heat and moisture and gas exchange occurring in an *in vivo* windrow. Therefore, it is vital that models are based on data derived from field observations and assessments so that the characteristics of the physical model reflect those of the actual practical composting system, which it is attempting to mimic.

In-Vessel Style Models

Pilot scale in-vessel systems are popular and have tended to feature in examples of physical models because they present an apparently ideal choice for such a scientific instrument, providing an easily controlled environment for the monitoring of selected physical or chemical parameters. Additionally, in-vessel composting plants are more industrially styled, which has perhaps naturally attracted more interest from engineers and hence, the development of models based more strongly along these parameters and ideologies than biological ones. The notion that in-vessel systems are "*high-tech*" and fit better into a pattern of being perceived as more "*scientific*" and open to systematic study, than windrows which are nominally "*low tech*" and "*natural*" or even just too complex could additionally explain the lack of specific windrow based physical composting models.

However, for a full understanding and further development of the composting process then a multi-disciplined approach is required.

The Lack of a Successful Windrow Based Physical Composting Model

The obvious lack of a successful physical composting model of windrow based composting is surprising given that windrow based composting is both one of the most traditional and well used systems in use today as well as one of the most versatile and robust (Robinzon *et al*, 2000; Rynk & Richard, 2001). A simple, economic to build and run model, which accurately models the characteristics of a windrow based composting system (such as microbially induced self heating), would be of great value to both the compost scientist and the commercial operator.

It seems clear that although composting is establishing itself more and more in the mainstream of sustainable waste management technologies, there is a danger that the good work of the last few years could be undone if commercial composters and perhaps more importantly *potential* large scale composters do not get the practical support they need to reliably, economically, safely and efficiently run a composting operation and produce a high quality marketable compost.

Compost researchers must use their increasing knowledge and understanding of compost science in a literally down-to-earth way and provide the compost site operators with practical guidance on how to achieve the above aims. The development of workable process standards and the methodology to allow compliance is one example. The enhancement of compost technologies through the use of novel model systems is another.

HYPOTHESIS

A review of composting literature suggests that for composting to continue to develop as a viable and sustainable waste management technology, there needs to be an increased knowledge and understanding of the temperature development and distribution patterns within the composting system known as open windrow composting. Currently, there is little detailed knowledge about the nature and behaviour of the microbially derived temperature profiles within windrows. The evolution of heat within windrows has long been recognised as a direct reflection of microbial activity (and hence, decomposition) and an indication of process stage. However, there has been a lack of detailed systematic studies of temperature within full size urban green waste derived windrows. Understanding of temperature development and distribution is of vital importance to improving the efficiency of composting operations (in terms of rate of decomposition, pathogen reduction, turning frequency etc) and the quality and safety of the final products. This will allow the development of practical process standards. Linked to the former (i.e. the requirement for enhanced knowledge of windrow temperature development and distribution) is the need for a realistic predictive physical model of the windrow based composting system. Current models are largely based on in-vessel systems and are technically flawed in certain aspects. The value to the composting / waste management industry of a practical predictive model is high, and its absence may in the future be a limiting factor on the continued development and success of composting.

This study aims firstly, to investigate in detail the distribution and development of temperature within large scale windrows in the field, with reference to physical, chemical, structural and climatalogical factors and to use these data to provide novel insights and techniques of value to the commercial composting industry. Secondly the study aims to employ the findings of the field trial based windrow temperature studies to aid in the development of a novel physical composting model, based on the behaviour of an open windrow composting system.

CHAPTER 2 – GENERAL EXPERIMENTAL METHODS

WINDROW SAMPLING AND COLLECTION

Samples of windrow material were removed on a weekly basis for the first eight weeks and at selected points thereafter, starting at windrow establishment, for physical and chemical analysis. Material was manually collected with the aid of a small trowel and gloved hands from six points; three equally spaced along each side (lengthwise) of the windrow at approximately 1m high at 0.5m deep below the surface. Individual samples were placed in labeled self-sealing plastic bags and frozen at minus 18°C (except those sub-samples required for moisture assessment, which was determined within 1 hour of collection) until required and subsequently defrosted.

pH ASSESSMENT OF COMPOST FEEDSTOCKS

Samples (10g ± 0.1g) of fresh field condition-feedstock samples were placed in previously acid washed 125ml plastic screw-top environmental bottles (Nalgene) in triplicate, to which was added 50ml of fresh water, pretreated *via* reverse osmosis (Elga, Vivendi Water Systems, High Wycombe, UK) and then deionised (Nanopure II, Barnstead International, Dubuque, USA) to 18MΩ. (hereafter, termed 18MΩ water). These were then hand-shaken for 2 minutes to create a homogenous suspension, before being left for 1 hour at room temperature to equilibrate, after which they were again hand-shaken for 2 minutes prior to reading. During this time the pH probe (Checker HI1270, Hanna Instruments Ltd., UK) was calibrated using pH 4.01 and pH 7.01 calibration solutions (Fisons Laboratory Reagent, Fisons Scientific Equipment, Loughborough, UK) following the manufacturer's instructions. The samples were then read three times in series, by placing the pH probe in the suspension and leaving for 30 seconds to stabilize before reading and recording. The probe was thoroughly washed with 18MΩ water between readings (Stenbro-Olsen, 1998).

MEASUREMENT OF CONDUCTIVITY WITHIN FEEDSTOCKS

Aqueous suspension samples previously prepared (as above) for pH determination were left overnight (18 to 24 hours) at room temperature. The following day these were then hand-shaken for 2 minutes prior to conductivity assessment. A conductivity probe with built in temperature compensation (HI9812, Hanna Instruments Ltd., UK) was calibrated following manufacturer's instructions, using a commercial calibration KCl solution (Hanna Instruments Ltd., UK) with a known conductivity value of 1413μS cm^{-1} and 18MΩ water. The probe was placed into each of the samples in turn and the value recorded (μS cm^{-1}). The probe was washed between readings with 18MΩ water. All samples were read in triplicate.

MOISTURE DETERMINATION OF FEEDSTOCKS

Samples of fresh feedstocks (approximately 15 to 25g wet weight) were placed in pre-dried and weighed paper bags and their mass determined and recorded, before being placed in an oven (Carbolite ELF 10/6, Carbolite, Hope, Sheffield, UK) at 103°C for 24 hours. The samples were removed from the oven and reweighed (taking into account the bag weight). The loss in mass on drying representing the moisture content (oven dried) of the samples. The resultant figures (g) were converted to percentage values (Gartland *et al*, 1997).

FEEDSTOCK BULK DENSITY CALCULATION

Samples of feedstocks were placed into a plastic beaker of known volume (100ml). These were placed on a previously tared balance to determine their weight or mass, after being gently tamped down to remove any large voids within the contents of the plastic beaker.

This allowed the calculation of the bulk density (the mass in a given volume) of the feedstock samples, initially expressed as a figure of x (g) (the weight of the material) per 100ml (the volume of the beaker). For convenience these were multiplied by ten as to express a bulk density figure in grams per litre (g l^{-1}) (Stenbro-Olsen, 1998; CEN TC233, 1993).

ORGANIC MATTER CONTENT OF FEEDSTOCK MATERIAL

Using oven-dried material derived from moisture content determination (see above), samples of approximately 1 to 2g (oven dry weight) were weighed out and placed into pre-weighed ceramic crucibles. These were transferred to a muffle furnace (Carbolite ELF 10/6, Carbolite, Hope, Sheffield, UK) at 600°C for 2 hours, after which they were allowed to cool in a desiccator before being weighed again. The loss of mass on heating, termed the loss on ignition (LOI) value, is representation of the organic matter content of the sample, in simple terms the fraction that can burn. The material, which is left, is termed the ash content and represents the non-organic or mineral fraction of the original sample.

The LOI values were calculated and then converted into percentages to give %LOI or % organic matter figures for the feedstock samples (Rowell, 1994). From these figures it is possible to calculate the approximate carbon content of organic matter by division by 1.8 (Polprasert, 1989).

HEAVY METAL ASSESSMENTS OF FEEDSTOCK MATERIAL

Samples of feedstock material were subject to heavy metal assessment *via* atomic absorption spectrophotometry (AAS) after extraction with EDTA (Ethylenediamine tetra-acetic acid).

EDTA Extraction Solution Preparation

A 0.05M solution of ammonia-EDTA (free acid) at pH 7 was prepared. This was achieved using the following methodology: 14.6g of EDTA (Fisher 'Certified' Chemicals, Fisher Scientific UK Ltd., Loughborough, UK) was weighed out and added to a 1l volumetric flask containing approximately 500ml of 18MΩ water which was then stirred. To this was added 8ml of ammonia solution (~35% SG 0.88) (Fisons Analytical Reagent, Fisons Scientific Equipment, Loughborough, UK), before adding more water to bring it up to around 950ml. The EDTA was allowed to dissolve and at this stage the solution was brought up to pH 7 with the addition of 1M ammonia and diluted to final volume (Rowell, 1994).

EDTA Extraction

Samples (10g ± 0.1g) were weighed out and placed in acid washed plastic screw top environmental bottles (Nalgene) to which was added 50ml of ammonia-EDTA solution. These were placed on a mechanical flask shaker at room temperature for 1 hour, before being decanted though Whatman No. 1 qualitative filter paper (Whatman International Ltd., Maidstone, UK) into fresh environmental bottles and the filtrate retained for analysis (Rowell, 1994).

Heavy Metal Determination Using Atomic Absorption Spectrophotometry (AAS)

The concentrations of zinc (Zn), copper (Cu), nickel (Ni), chromium (Cr), cadmium (Cd) and lead (Pb) were determined using AAS (Perkin-Elmer Model 1100B, Perkin-Elmer & Co., GmbH, Uberlingen, Germany). Calibration standards were prepared for each metal using commercial AAS standard solutions (Johnson Matthey, Karlsruhe, Germany) in ranges appropriate to each metal following AAS manufacturer's guidance and were used to calibrated the machine. Wavelengths and other parameters used were those preset by the equipment as optimal for each of the metals. Background correction was used and the acetylene /air ratio was 2.5l / 8.0l minute^{-1} for all metals except chromium for which a 5.0l / 9.5l minute^{-1} mix was used. The system was flushed with 18MΩ water between readings (Perkin-Elmer, 1982; Clesceri *et al*, 1989; Rowell, 1994).

Samples were read sequentially in triplicate for each metal, and, where required, dilutions were prepared using the extraction solution before being recorded. From these data it was possible to calculate the concentration of metal EDTA extractable within the original feedstocks. This was expressed as mg of heavy metal per kg of feedstock (mg kg^{-1} fresh weight).

ACID WASHING OF GLASS AND PLASTIC WARES

All plastic and glassware used for the physical – chemical assessments outlined above were acid washed before use, using a 2.5% nitric acid solution (prepared from concentrated nitric acid (~70% SG 1.42) (Fisher Chemicals, Fisher Scientific UK Ltd., Loughborough, UK) and 18MΩ water)) contained within a large lidded plastic container acting as an acid bath. Items were initially washed and rinsed with tap water before being placed in the acid bath for a minimum period of 24 hours. After this they were removed and thoroughly rinsed with 18MΩ water after which they were allowed to air dry before use or storage.

STATISTICS

All experiments in this project were designed to allow for statistical analysis. Experimental data presented in this study were derived from the mean of a minimum of triplicate data sets. Where shown, error bars are derived from the standard error of the data set.

CHAPTER 3 –TEMPERATURE AND PHYSICAL-CHEMICAL STUDIES OF WINTER AND SUMMER WINDROWS

INTRODUCTION

POPULARITY AND IMPORTANCE OF OPEN WINDROW COMPOSTING

Open windrow composting of green wastes collected *via* civic amenity sites, household collections, (e.g. compostainer wheeled bins), local authority parks departments and private gardening contractors, as well as related industries, is currently the major form of commercial scale composting in the UK (Slater *et al*, 2001) and a similar picture can be described elsewhere.

Advantages of the Method

An open windrow composting operation is appealing to potential composters because it is, essentially, relatively low cost in both investment and running terms and low tech in operation, but can still recycle large volumes of waste material in a reasonably short time to produce a marketable end product. It is reasonable to suggest that these factors will result in the adoption of this style of composting for the foreseeable future, as the level of compost production increases due to the need for more sustainable forms of waste management as outlined in Chapter 1, because in-vessel composting is (certainly in the UK) still a more expensive option and more technically demanding than open windrows.

Demands on the System

However, for open windrow composting to meet the demands of the modern waste management industry and the end product market, in terms of process efficiency leading to a high quality, safe and reliable compost, then it is vital that there is a comprehensive understanding of "*what goes on inside the windrow*".

IMPROVED KNOWLEDGE OF WINDROW TEMPERATURE CHARACTERISTICS KEY TO SUCCESS

The production of microbially derived heat and the resultant rise in temperature within the waste materials is perhaps the most characteristic feature of composting and is well documented (leading to the generalized outline of the composting process described in the introductory chapter). It has however, been rarely studied in any detail in the field using large-scale windrows (Stenbro-Olsen *et al*, 1995; Joshua *et al,* 1998). The need for detailed information about the heating and patterns of temperature development is paramount, because it is key to improving the composting process, in terms of operational efficiency, product safety and quality and additionally, in the development of effective laboratory based models capable of accurate prediction of the aerobic biodegradation of any potentially compostable waste materials.

Experimental Rationale

To this end, a series of experiments was envisaged, whereby large-scale windrows would be established at different times of the year in such a way that detailed monitoring of windrow temperature could be achieved. These would provide both an unprecedented view of temperature development and patterns within the windrows and provide valuable raw data for the design of a realistic laboratory model of the open windrow composting process.

METHODS AND MATERIALS

ESTABLISHMENT OF FIELD TRIALS

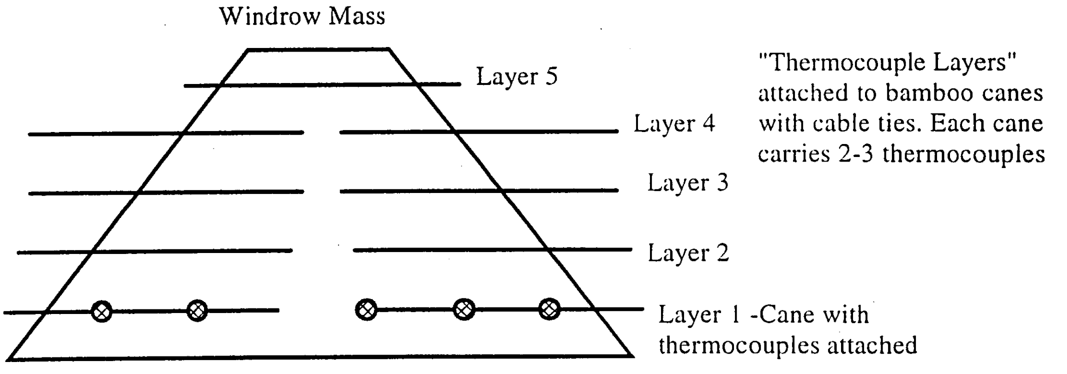
Feedstock origin and preparation

Field trials were established in February (Field Trial 1 - winter) and August (Field Trial 2 - summer) 2000. The Environmental and Consumer Protection Department of Dundee City Council, Scotland, UK, provided the green waste material, machinery and personnel for the production of the experimental windrows at their composting site at Wright Avenue, Riverside, Dundee. The green waste utilized was material available seasonally on site, diverted from the Council's Discovery Compost programme. It was derived from domestic and gardening wastes *via* Dundee's civic amenity sites, city-wide household compostainer collections (source-separated biodegradable wastes, comprising of small scale gardening wastes and household fruit and vegetable waste collected in specialised 140l Schaefer Compostainer wheeled bins; SSI Schaefer, Basingstoke, Hants, UK) and private commercial gardening contractors. This material was mechanically shredded and mixed on site using a TIM SD2000 shredder (Tim Maskinfabrik A/S, Fabriksvej 13, Denmark).

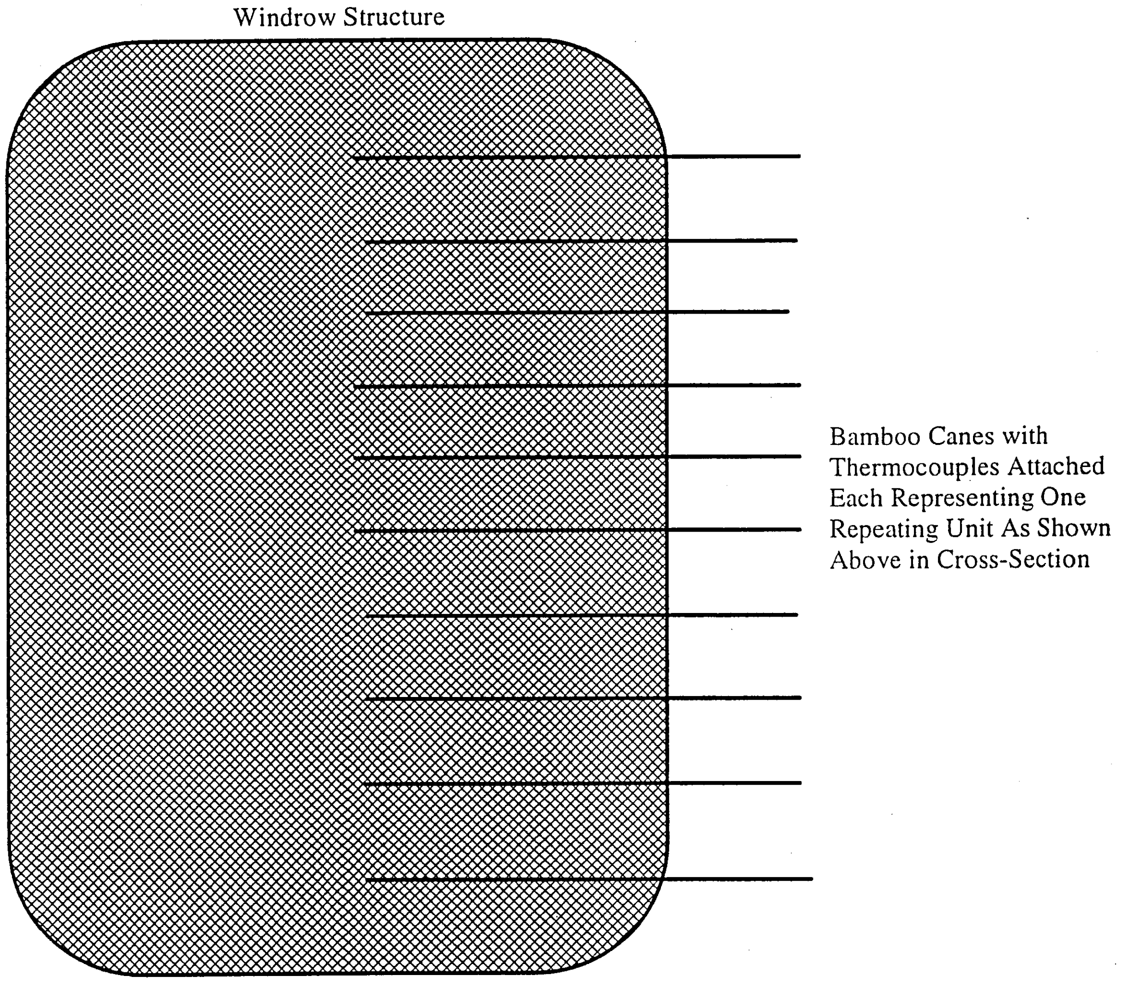
Temperature Probe Configuration

Approximate dimensions for the February windrow were 12m long by 5.5m wide (at base) and 2.5m high with a pyramidal cross section. In order to facilitate the measurement of temperature within the windrows, Type K 2m long, PVC coated individually numbered thermocouples were purchased (Kalestead Ltd., Braintree, Essex, UK). Thermocouples were arranged in a series of ten repeating equidistant cross sectional units, with five thermocouple-layers (0.2m (Layer 1), 0.5m (Layer 2), 1m (Layer 3), 1.5m (Layer 4) and 2m (Layer 5) vertically apart). Thermocouples were arranged at the following depths; Layers 1 and 2; 0.5m, 1m and 2m, Layers 3 and 4; 0.5m and 1m, and Layer 5; 0.5m below the surface lengthways along the windrow (180 thermocouples in total). The thermocouples were attached with plastic cable ties to 2.14m long supporting bamboo garden canes. Figure 5 provides a general schematic representation of the thermocouple arrangements for the field trials (detailed diagrams of the thermocouple arrangements for each of the layers appear in conjunction with Figures 9 to 13).

Figure 5: Generalised Field Trial Thermocouple Arrangements within Field Windrows for the Assessment of Temperature



Cross-Section of Field Trial Windrow Showing General Arrangement of "Thermocouple Layers" of One Repeating Unit (Total 10) (Not to Scale)



Plan of Field Trial Windrow Showing General Arrangement of "Repeating Units" of Thermocouples Attached to Canes (Each Side Identical - One Side Only Shown) (Not to Scale)

Windrow Construction

The windrow was constructed in a series of layers thus a Liebherr 531 wheeled loader (Liebherr-Werk Bischofshofen GmbH, Bischofshofen, Germany) was used to prepare a base layer of shredded material, approximately the base dimensions of the proposed windrow along a north–south alignment. On top of this were placed the canes carrying the thermocouples for the lowest regions of the structure (Layer 1). Another layer of material was added and gently compressed before the second layer of canes was introduced, this process was repeated until all the thermocouples were incorporated and the desired final height of the windrow was reached (2.5m). Any cane ends / thermocouple plugs which had become partially covered during construction were cleared and the windrow was allowed to settle overnight. Plate 1 shows the completed Field Trial 1 windrow shortly after establishment in February 2000.

Field Trial 2 Establishment

The windrow established in August 2000 (Field Trial 2 - summer) was constructed in a similar manner to the former. However, owing to slightly reduced dimensions (10.5m long by 4.25m wide and 2m high) a lesser number of thermocouples (140) were employed in the following arrangement of ten repeating units of three thermocouple layers vertically separated at 0.3m (Layer 1), 0.75m (Layer 2) and 1m heights (Layer 3). Layer 1 exhibited horizontal thermocouple spacing of 0.5m, 1m and 1.5m depth below the surface, while layers 2 and 3 employed 0.5m and 1m intervals (details of thermocouple arrangements appear with Figures 16 to 22).

TEMPERATURE DETERMINATION AND RECORDING

Starting the following day, in both trials, (Day 1) temperature readings were taken from each of the thermocouples on a daily basis, Monday to Friday mornings (access to the site being restricted at the weekend for safety reasons). A Digitron 2088T handheld Type K

Plate 1: Field Trial 1 (winter) Experimental Windrow 1 week old looking south-east, showing bamboo canes supporting the thermocouples.

thermocouple datalogging thermometer was used to take the measurements, before downloading into a PC *via* a Digitron infrared Digilink unit. Data were captured and stored using Digitron Digilog V1.09 software (SIFAM Ltd, Torquay, Devon, UK). Data from this program was exported to Microsoft Excel 97 (Microsoft Corporation, Redmond, USA) for further analysis.

Climatological Data

Ambient (air) temperature at the windrow site was also recorded daily (during the morning) using an additional thermocouple attached to a vertically positioned garden cane adjacent to the windrow. Weather data (including wind speed and direction) from the adjacent Dundee Airport were downloaded from the Internet- (National Weather Service, Internet Weather Source, Current Weather Conditions – Dundee / Riverside, United Kingdom; http://weather.noaa.gov/weather/current/EGPN.html.)

WINDROW SAMPLING AND COLLECTION

Samples of windrow material were removed on a weekly basis for the first eight weeks and at selected points thereafter, starting at windrow establishment, for physical and chemical analysis employing the technique outlined in the General Experimental Methods chapter.

PHYSICAL –CHEMCIAL TESTING OF WINDROW MATERIAL

A suite of physical-chemical assessments were carried out on the collected samples *viz.* pH, conductivity (μS cm^{-1}), % moisture content, % organic matter, bulk density (g l^{-1}), and selected heavy metal concentration *via* EDTA based extraction (mg kg^{-1} fresh weight) using the methodologies outlined in Chapter 2. These were performed on a minimum of three sub-samples from each of the six main samples read in triplicate. The data gained from these individual measurements were pooled to derive mean figures for each of the weekly-collected windrow samples.

SURVEYING OF WINDROW STRUCTURE

In order to gain information regarding overall structural changes to the windrows over time, a surveying technique termed electronic tacheometry was performed to record data points in three dimensions. A series of base stations (fixed reference points) consisting of concrete blocks with metal rods projecting a short distance vertically were inserted into the ground around the windrow. A Sokkia SET4 total station theodolite (Sokkia Ltd., Crewe, UK) was positioned over a base station and using a handheld prism reflector on a ranging pole positioned on each station in turn, the relative positions of each of the fixed reference points were acquired. The prism reflector was then systematically positioned around the base of the windrow and then progressively higher over the surface of the structure following the contours, and the positions recorded by the SDR datalogger (Sokkia Ltd., Crewe, UK) linked total station theodolite. SDR software (Sokkia Ltd., Crewe, UK) was used to process the data and produce a contoured plot of the experimental windrows. This was carried out within two days of establishment of each of the field trial windrows and then again at a later time period.

RESULTS AND DISCUSSION

GENERAL MEAN-TEMPERATURE TRENDS OBSERVED IN WINTER & SUMMER WINDROWS

Following daily monitoring of the temperature probes within the test windrows, the collected data were pooled and used to derive daily mean temperature figures representing the overall or *average* temperature of the relevant experimental windrow. Figure 6 shows such data for Field Trials 1 and 2 (winter and summer) along with the related ambient temperatures for days 1 to 38. It was clear in both cases that active exothermic composting activity occurred as the mean windrow temperatures showed prolonged periods above the ambient temperature observed. Both field trials mean windrow temperature plots show a representation of the generic *pattern* of temperature trends within a composting system as shown earlier in Figure 4, especially that of Field Trial 1. A rapid rise in temperature over days 1 to 3 followed by a depression between days 5 to 10, before a temperature elevation and peak at day 20, then decline back to ambient, was observed. This strongly confirms the link between microbial activity, succession and temperature trends within the composting mass, the indigenous mesophilic microbes producing an initial burst of activity (revealed here as rapidly increasing temperature) followed by a period of mixed activity when mesophiles are declining and thermophilic organisms are ascending (the dip on the plot) and then thermophilic activity and eventual decline. Early research by Carlyle & Norman (1941) had demonstrated that in small-scale systems the temperature increase was not linear and consisted of two flattened sigmoid curves. When plotted as rate of temperature evolution these peaked at 40°C and 60°C. They surmised correctly that this was caused by two distinct populations of microorganisms with a successional period between. The data presented here confirms this in a full size field system, derived from a level of temperature assessment normally only possible in laboratory environments.

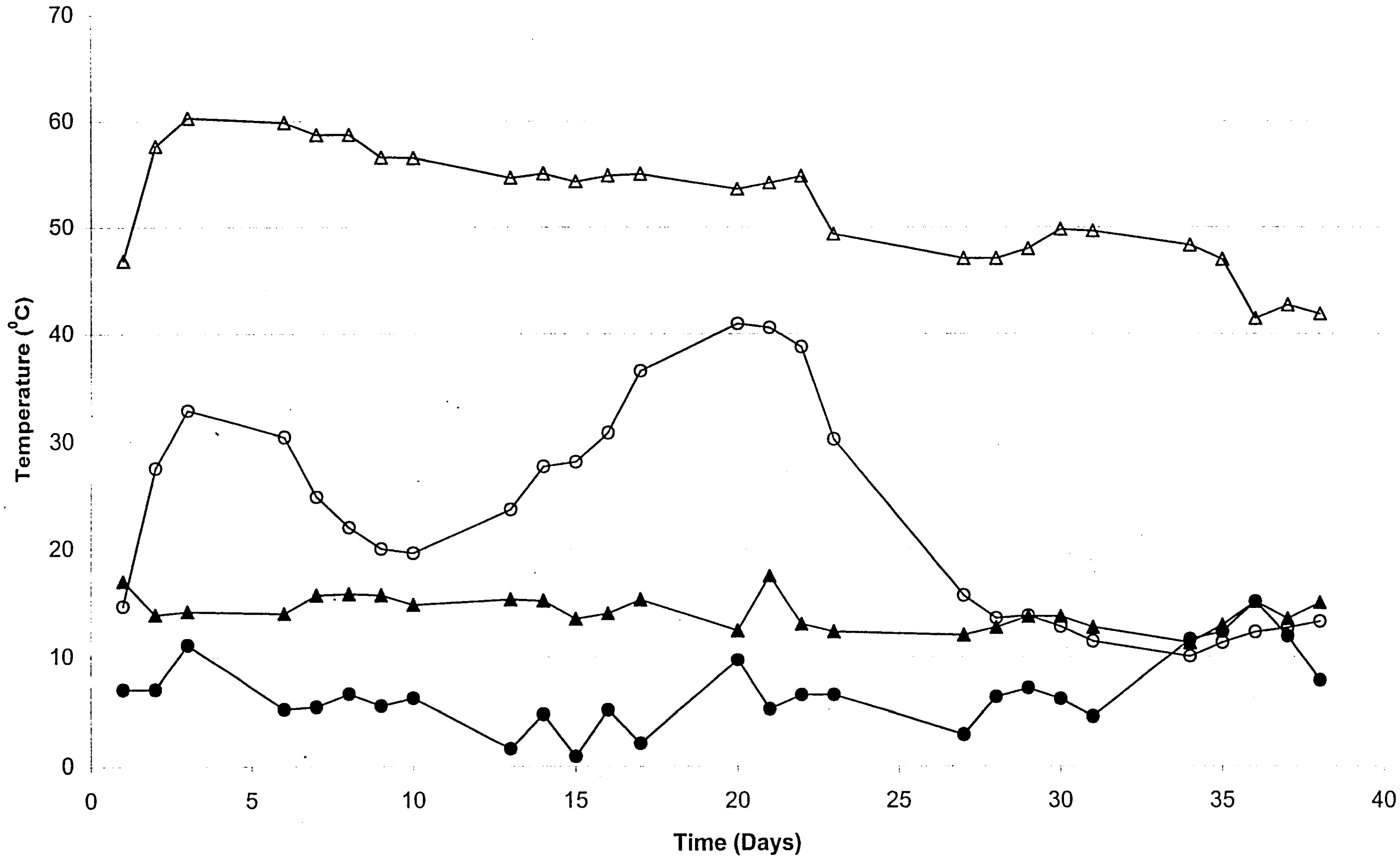
Figure 6: Riverside composting Field Trials 1 and 2 (winter and summer). Mean overall windrow temperatures (°C) and ambient (air) temperatures (°C) over Days 1 to 38 of each field trial.

(○) Mean windrow temperature (°C) field trial 1 (winter)

(●) Ambient (air) temperature (°C) field trial 1 (winter)

(△) Mean windrow temperature (°C) field trial 2 (summer)

(▲) Ambient (air) temperature (°C) field trial 2 (summer)



Temperature (^{0}C)
70
60
50
40
30
20
10
0
0
5
10
15
20
25
30
35
40
Time (Days)

The plot derived from Field Trial 2 data presents an initially, more complex scenario with an apparently less obvious successional pattern. A similar but "flattened" pattern of rapid rise, plateau, dip, second peak and decline from day 20 was also observed in this data set. It would appear based on these data that the period of succession between the mesophilic and thermophilic communities was very short and that thermophiles became established very quickly. This would indicate that conditions suitable for both rapid decomposition and effective pathogen reduction were quickly established within this windrow.

From these data plots there is a strong indication that day 20 is a critical time, as it is from this period that, in both cases, there was a prolonged decline in the mean temperature of the windrows, and that three weeks represents a natural turning cycle for this size and type of windrow, if optimum degradative temperatures are to be maintained within the windrow. This represents a longer period before initial turning than is often reported, where cycles of as short as 48 to 72 hours are indicated (Composting Association, 2002). However, it does not consider factors such as the mixing of the contents of the windrow for the enhancement of pathogen reduction. However, it does demonstrate the length of time windrows of this nature maintain a natural initial active phase and therefore, indicates that in gross terms microbial nutrient supply and growth conditions within the windrow must have been adequate until at least this point (Day 20). This could be useful in the calculation of the economical deployment of manpower and equipment at composting sites for turning purposes, if optimum conditions can be initially established and methodologies can be developed which can assess whether these are being maintained, then unnecessary turning operations could be eliminated.

THE VALIDITY OF OVERALL MEAN TEMPERATURE PLOTS FOR WINDROW TEMPERATURE ASSESSMENTS

Graphs of the average temperature of compost windrows are the generally quoted norm for assessing the composting process and the obtaining of effective pathogen reduction temperatures. However, can this be considered to be acceptable, especially when used in a simplistic fashion, or should a more precautionary attitude be taken, when attempting to meaningfully assess the nature of temperature development and distribution within a typical windrow structure?

The plots of mean windrow temperature from Field Trials 1 and 2, present two quite different temperature regimes, the winter field trial showing an essentially low temperature mesophilic pattern and the summer trial revealing a defined high temperature thermophilic plot. From this information it would appear that Field Trial 1 had failed to reach thermophilic conditions and therefore, would not represent a successful composting operation in terms of decomposition efficiency and pathogen control (Table 2). Field Trial 2 represents the opposite of this condition, clearly meeting many of the national standards presented in Table 2. The apparent differences between the two trials could be explained, in part by the potentially poorer quality feedstocks available in the winter months, with their higher woody material content (Gartland *et al,* 1997). This results in a less favourable C:N ratio and a lower level of biodegradability (Stenbro-Olsen *et al*, 1995) when compared to the more diverse and nitrogen rich "green" material (resulting in rapid heat evolution and easier-to-compost wastes) available in the summertime. The work of Gartland *et al,* (1997) revealed clear seasonal variation and flows in the mix of wastes entering the Discovery composting programme over a typical year. However, is this a realistic picture of the temperature conditions within typical windrows or is there a more complex temperature pattern than is presented by plots of mean windrow temperature that is vital to improved process control?

Figures 7 and 8 show mean temperature trends for each of the different vertical layers where thermocouples were positioned, along with ambient temperature. These data reveal a more complex pattern of temperature profiles within the experimental windrows and the importance of appreciating the distribution of temperatures throughout the composting structure.

The data from Field Trial 1 (Figure 7) show a distinctive distribution with different layers (i.e. heights) within the windrow showing variation in daily mean temperature. This indicates that there were cool and hot zones within the structure. It would appear that the middle zone of the windrow (Layer 3: 1m high) had the greatest mean temperatures with Layers 1 and 2 (0.2m and 0.5m high respectively) closely allied. This suggests that commercial composters should avoid favouring the central core regions of a windrow when assessing temperature, as this would result in unrealistically high mean values. This is commonly regarded as the ideal location for temperature measurement, but these data demonstrate that it is likely to induce bias into the results. The generally trapezoidal shape of a windrow (i.e. being wider at the base than the top) means the majority of the volume of material resides in the lower regions of the structure and therefore, it is important that the temperature and the microbial activity (both in terms of decomposition and pathogen proliferation) there is effectively monitored. The upper areas of the windrow, where there was a lesser cross-sectional depth (and therefore, less insulation and greater potential heat loss) did not exhibit such high temperatures. Feedstocks in these zones would therefore degrade at a slower rate and less well. The convectional movement of heat (the chimney effect) from the bottom to the top of the windrow resulted in hot air escaping from the upper ridge (observed as rising water vapour – field observation). This would have resulted in increased heat loss from these areas by latent heat of evaporation, especially during periods of low ambient temperature. Layer 5 (2m high) maintained this repressed temperature trend throughout the trial. However, it must be noted that during the active phase of the trial the mean temperature in this layer was always above the ambient temperature (and exhibited a similar pattern over time as the other layers) and peaked at 27.3°C, clearly above the ambient level of 6.5°C. This strongly indicates that active exothermic microbial activity was occurring in this zone, but that temperatures above

Figure 7: Riverside composting Field Trial 1 (winter) Windrow temperatures (°C) are described by reference to mean temperatures at five heights termed layers where thermocouples were positioned at varying depths, additionally the overall mean windrow and ambient (air) temperatures (°C) are given for days 1 to 38 of the trial.

Layer 1 indicates temperature readings from a height of 0.2m and depths of 0.5m, 1m and 2m. Layer 2 indicates temperature readings from a height of 0.5m and depths of 0.5m, 1m and 2m. Layer 3 indicates temperature readings from a height of 1m and depths of 0.5m and 1m. Layer 4 indicates temperature readings from a height of 1.5m and depths of 0.5m and 1m. Layer 5 indicates temperature readings from a height of 2m and a depth of 0.5m.

(○) Layer 1 mean temperatures (°C)

(△) Layer 2 mean temperatures (°C)

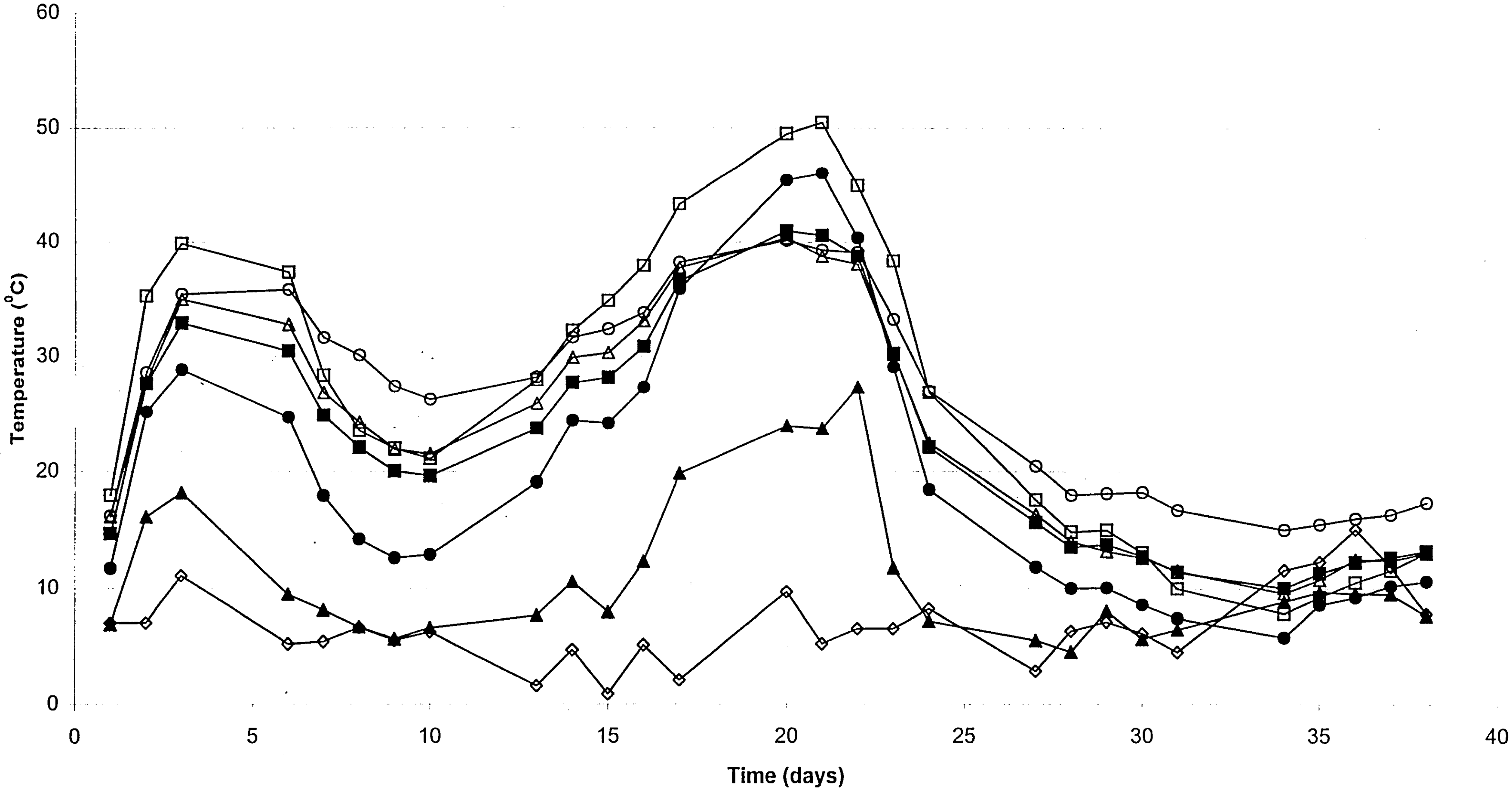
(□) Layer 3 mean temperatures (°C)

(●) Layer 4 mean temperatures (°C)

(▲) Layer 5 mean temperatures (°C)

(■) Mean overall windrow temperature (°C)

(◇) Ambient (air) temperature (°C)



60
50
40
30
20
10
0
Temperature (°C)
0
5
10
15
20
25
30
35
40
Time (days)

Figure 8: Riverside composting Field Trial 2 (summer) Windrow temperatures (°C) are described by reference to mean temperatures at three heights termed layers where thermocouples were positioned at varying depths, additionally the overall mean windrow and ambient (air) temperatures (°C) are given for days 1 to 58 of the trial.

Layer 1 indicates temperature readings from a height of 0.3m and depths of 0.5m, 1m and 1.5m. Layer 2 indicates temperature readings from a height of 0.75m and depths of 0.5m and 1m. Layer 3 indicates temperature readings from a height of 1m and depths of 0.5m and 1m.

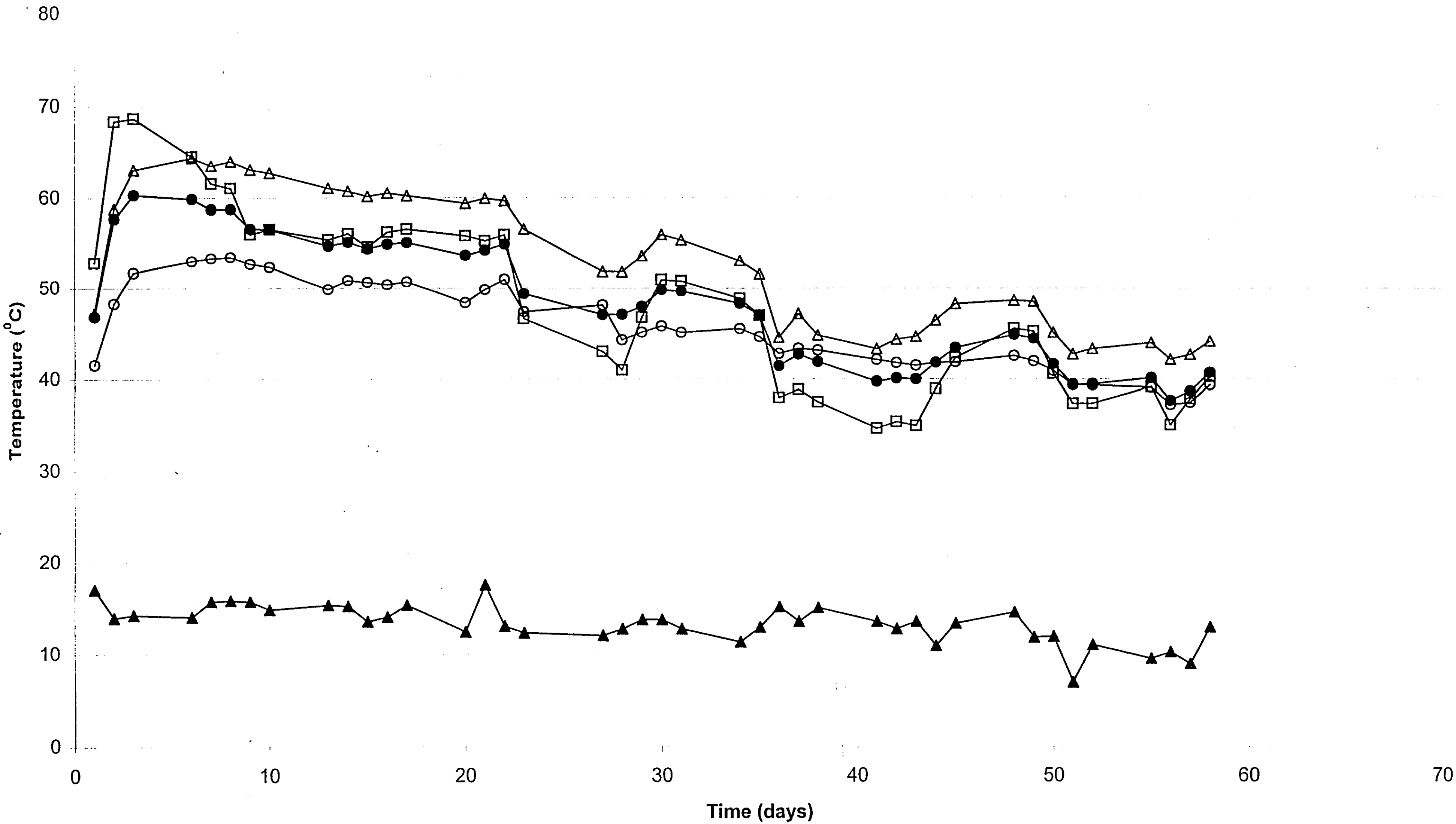
(○) Layer 1 mean temperatures (°C)

(△) Layer 2 mean temperatures (°C)

(□) Layer 3 mean temperatures (°C)

(●) Mean overall windrow temperature (°C)

(▲) Ambient (air) temperature (°C)


80
70
60
50
40
30
20
10
0
Temperature (°C)
0
10
20
30
40
50
60
70
Time (days)

above these levels did not develop due to heat loss in excess of heat production because of the physical location of this layer of material. Layer 4 (1.5 high) showed a burst of thermal activity during Days 10 to 21, becoming the second hottest region. This probably reflected the overall increased metabolic activity occurring in the windrow at this period, which corresponded to the thermophilic phase of the composting process where "*heat-loving*" organisms predominate and rapid degradation of the organic waste material occurs. The heat radiated out from the hotter central areas into the upper region (hot air rises). The layers were only separated by 0.5m vertically from each other, which would have resulted both in directly increased temperatures, and also the development of conditions suitable for the growth of thermophilic organisms and hence, more heat production.

An important aspect of effective composting is the sustained development of thermophilic conditions within the windrow. This is essential if the rapid and efficient degradation of the waste materials is to be achieved and if potential pathogens (human, animal and plant) as well as weed seeds are to be controlled or eliminated from the final product (Stenbro-Olsen *et al*, 1995). These results show such conditions were not achieved, even during the hottest phase (around Day 20 to 21) in this test windrow. The central Layer 3 achieved 50°C with Layer 4 in the mid-40°Cs, but there was no retention of these temperatures, which is required for pathogen reduction. Additionally, large zones within the windrow did not reach these hotter temperatures. Layers 1 and 2, representing areas with large cross-sectional masses, peaked at approximately 40°C, an ideal temperature for the development and proliferation of human and animal pathogens. The results revealed the spatial distribution of heat and hence, microbial activity within the windrow. Although some variation in temperature would logically be expected throughout a structure like a windrow, the results indicated there was a high level of variation in the patterns of heating within the structure which were not revealed in simple overall mean temperature plots. This is even more acute when it is considered that in this study the overall mean temperature was derived from over 100 daily data points and typically, commercial composters employ single figure numbers of temperature readings to derive mean windrow temperatures, (e.g. the UK Composting Association suggest six data points per windrow; Composting Association, 2002). Therefore, these results demonstrate the need for careful and thorough measurement of temperature within such masses.

Potential reasons for some of the heterogeneous temperature trends observed include, the mixing and distribution of the waste materials and the internal structure of the windrow. Pockets of poor construction, (i.e. areas without suitable air spaces for the movement of gases and moisture) could lead to patches that were anaerobic and or micro-water-logged, both of which reduce the efficiency of the aerobic composting process and therefore, the production of heat. Over compression of the lower regions of the windrow (by the sheer weight above) could result in similar conditions (Das & Keener, 1997; Joshua *et al*, 1998) and this can be observed in the somewhat depressed temperatures recorded in Layers 1 and 2.Conversely, the upper layer with its less compacted nature (lower bulk density) could lose heater faster due to its lower heat storage capacity (Stenbro-Olsen, 1998). This may be an important consideration when constructing operational windrows, which may not be noticed in small-scale experiments. The use of a field trial situation rather than a laboratory one allowed the clearer observation of temperature trends, particularly those potentially related to mass and volume.

The results demonstrate the importance of windrow turning. In the trial the windrow was not turned and this resulted in part in the limited thermophilic phase observed and the rapid return to ambient temperatures. Turning of the feedstocks (around Day 24) would have exposed new surfaces for microbial attack, both by breaking up the existing material as well as mixing in the wastes from the cooler regions to the more insulated hotter core areas and would have potentially improved the structure of the windrow – removing the areas of poor porosity and over compression. It can be noted that the main reason for turning windrows is not to introduce oxygen directly, but to improve overall internal structure and hence, gas exchange. This may have allowed a third temperature peak to develop and prolonged the vital thermophilic phase. The windrow was turned on Day 42 and a third elevated temperature peak developed after a delay which was caused by the windrow's return to ambient and therefore, the need to re-start the process (data not shown).

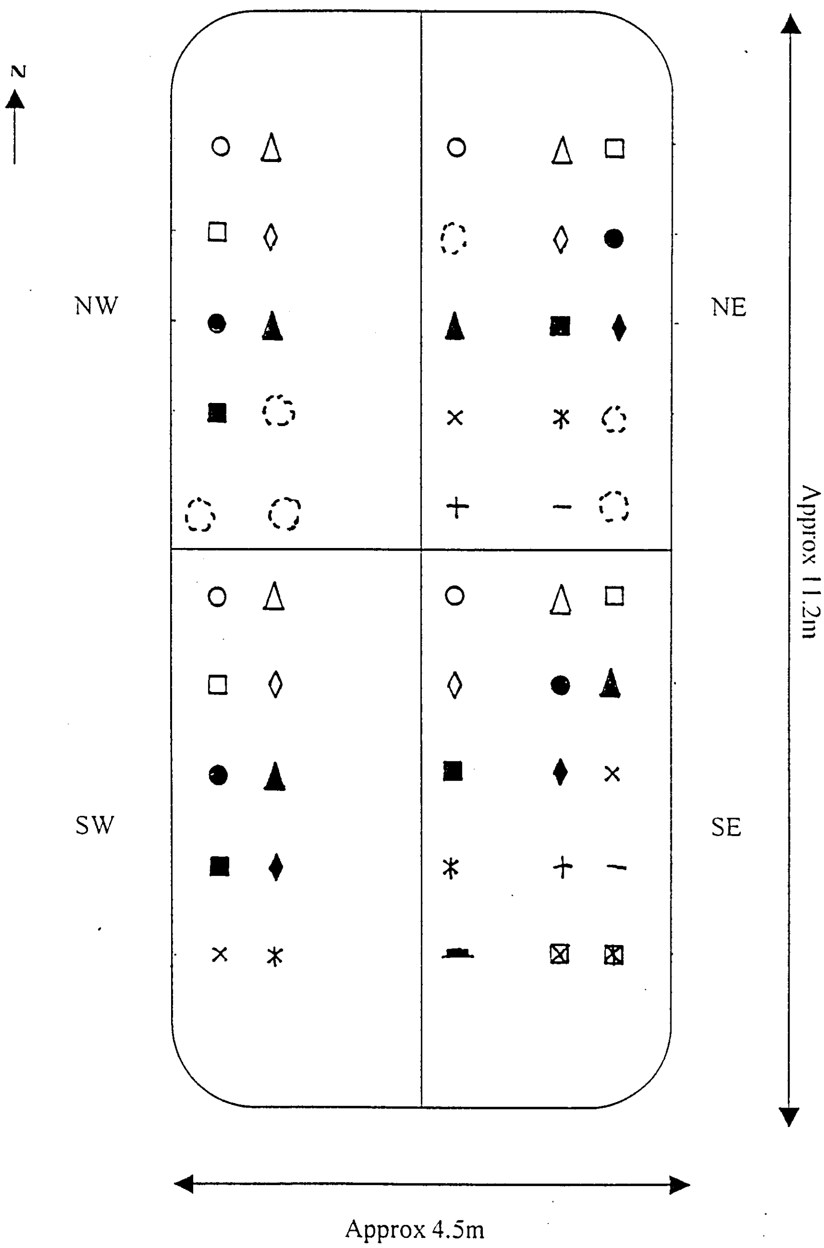
The second field trial data (Figure 8) also exhibited an initial rapid rise in temperature in all the thermocouple layers. This was again followed by a decline (thermal inactivation of the mesophiles) before a long period of thermophilic conditions (with thermophiles as the dominant organisms). After Day 21, there was a depression in temperature levels followed by a minor peak and another trough. This was similar in time span to the decline observed in Field Trial 1 data. It is noticeable that from Day 35 onwards there was a general downward trend in the temperature and a narrowing of the differences between the measurement zones. This indicated the conditions in the windrow were continuing to decline and be more unfavourable to thermophilic degradative organisms, but presumably physically more uniform (due to the decomposing activity of the thermophiles) which is the expected trend as a heterogeneous mix of feedstocks is converted into a more homogenous compost. However, even at Day 58 mean temperatures were still in the region of 40°C, compared to around 10°C during Field Trial 1 after only 38 days.

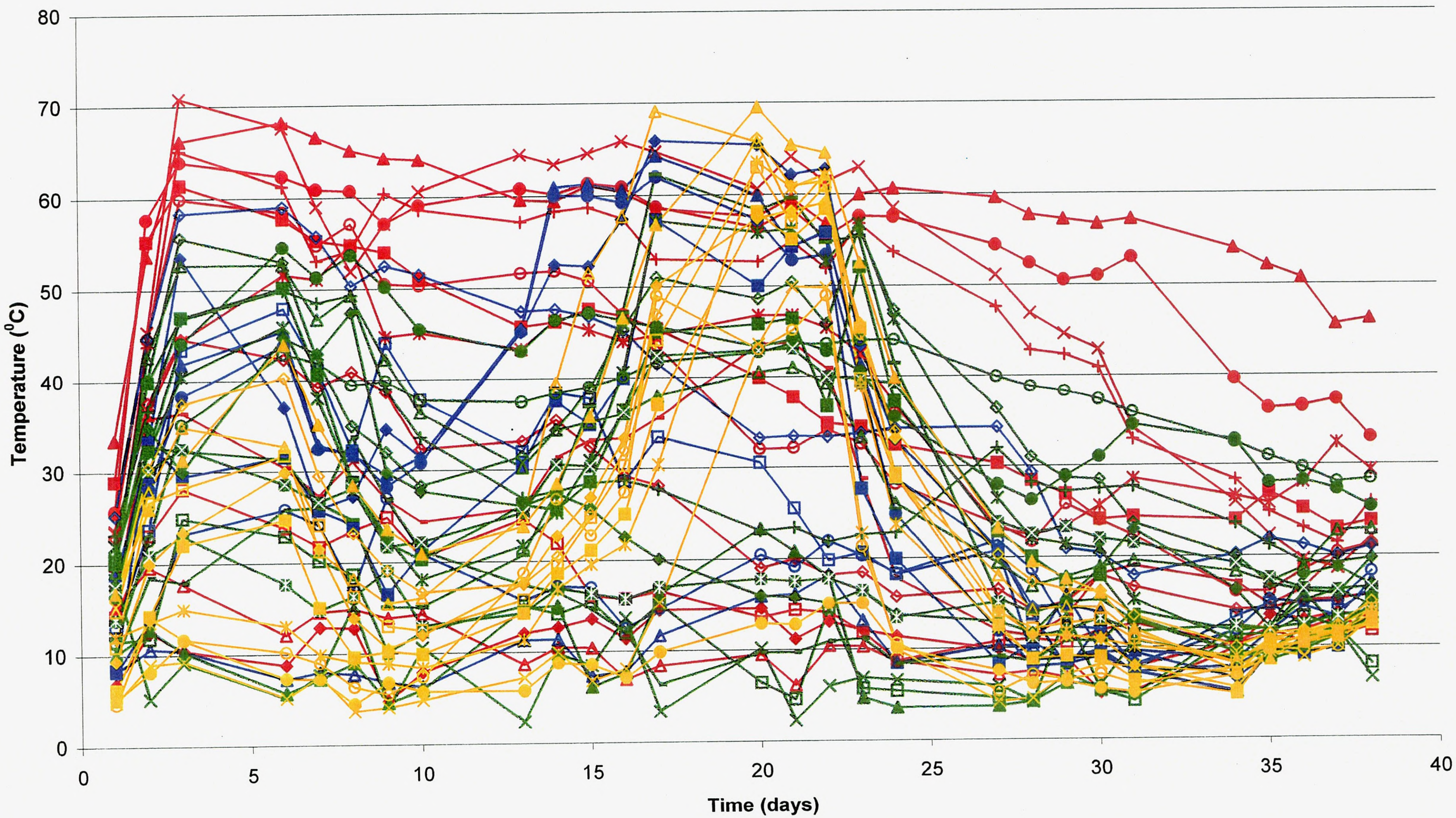
When compared to the overall mean plot data for the second trial (Figure 8, mean overall windrow temperature), it is clear that are there are features revealed in the plots of the individual layer's mean temperatures (Figure 8, mean layer temperatures) not seen in the former plot, these include the more pronounced depression of temperatures (especially at the 1m high zone after the initial peak; similar to that observed in Field Trial 1 layer 3). This suggests the death of the indigenous mesophilic microorganisms after rampant exothermic metabolic activity. In Field Trial 2 all layers of the windrow quickly reached and maintained thermophilic temperatures, indicating better quality feedstocks and perhaps improved windrow structure compared to the first winter based trial. It was again the middle layer (Layer 2) of the windrow that exhibited the highest prolonged temperatures and represented the most active region of the windrow. Interestingly, during the main active phase all of the layers maintained mean temperatures within a range of approximately 50°C to 60°C, which is very much within the temperature range described as optimal for the degradation of biowaste and also the one where the widest range and highest numbers of microorganisms exist (Tiquia *et al,* 2002; Day & Shaw 2001). Conditions within the windrow during this time were presumably capable of supporting a high level of microbial activity (to produce the heat), but also physically structured such as to allow the controlled release of this heat to the environment over time (heat retention *vs.* heat loss). The depression in temperature at around three weeks was clear and suggests that conditions became progressively more unfavourable for the growth of the initial set of thermophilic microbes. The recovery in temperatures at around day 30 suggests that a succession to a different group of microorganisms (different thermophiles more suited to the current environment), which again, *via* growth and metabolism, caused a temperature increase. This pattern of dip and peak continued to repeat itself, however, the general temperature trend was downward, suggesting overall that readily available and degradable nutrients were progressively depleted within the most actively decomposing regions, again indicating the need for turning and mixing of the windrow contents. These data support the research of Stenbro-Olsen (1998) who described the cyclical nature of the development of changing microbial communities and temperature trends within windrows.

FIELD TRIAL 1: ANALYSIS OF TEMPERATURE TRENDS IN WINDROW LAYERS BY QUARTERS (NE, NW, SE, and SW)

Figures 9, 10, 11, 12 and 13 describe the individual temperature trends for each of the thermocouples within a layer at a set height and varying depth, arranged by dividing the windrow into quarters, termed NE, NW, SE and SW related to their geographical location, noting that the experimental windrow was constructed along a north-south axis. Different colour groups have been used to emphasize / clarify the different geographic zones.

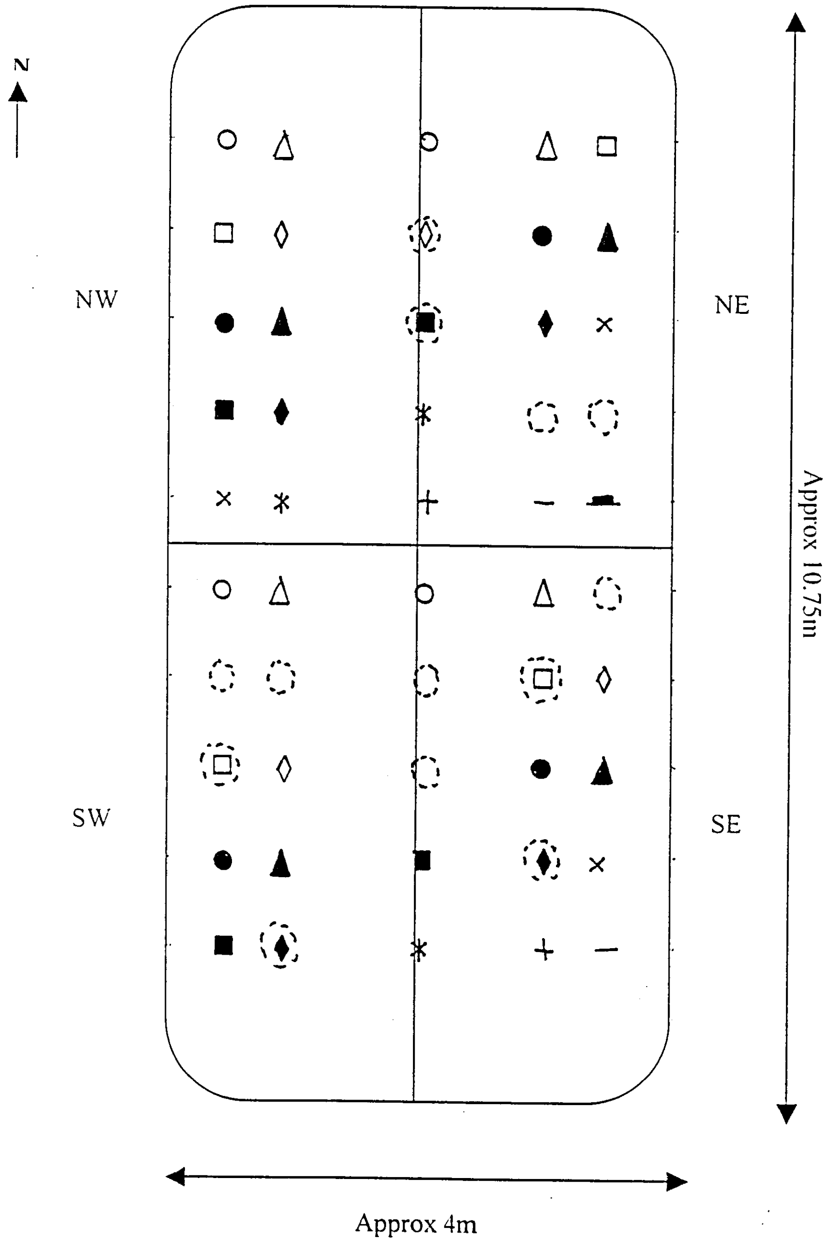
Figure 9: Riverside composting Field Trial 1 (winter) windrow temperatures (°C) Layer 1 (0.2m high) arranged by geographic quarters (NW, NE, SW, SE) over Days 1 to 38. Temperature trends from operational thermocouples as described in the diagram below are shown in relationship to their location within the windrow structure (approximate dimensions given (m)). The following colours have been used to represent the windrow regions: Blue (NW), Red (NE), Yellow (SW), Green (SE).
NW quarter thermocouples (with depth shown) (○ 0.5m) (△1m) (□ 0.5m) (◇ 1m) (● 0.5m) (▲ 1m) (■ 0.5m)
NE quarter thermocouples (with depth shown) (○ 2m) (△1m) (□ 0.5m) (◇ 1m) (● 0.5m) (▲ 2m) (■ 1m) (◆ 0.5m) (× 2m) (✳ 1m) (+ 2m) (-1m)
SW quarter thermocouples (with depth shown) (○ 0.5m) (△1m) (□ 0.5m) (◇ 1m) (● 0.5m) (▲ 1m) (■ 0.5m) (◆ 1m) (× 0.5m) (✳ 1m)
SE quarter thermocouples (with depth shown) (○ 2m) (△1m) (□ 0.5m) (◇ 2m) (● 1m) (▲ 0.5m) (■ 2m) (◆ 1m) (× 0.5m) (✳ 2m) (+ 1m) (-0.5m) (▪ 2m) (☒1m) (⊠0.5m)
◌ Indicates thermocouples yielding partial data sets.

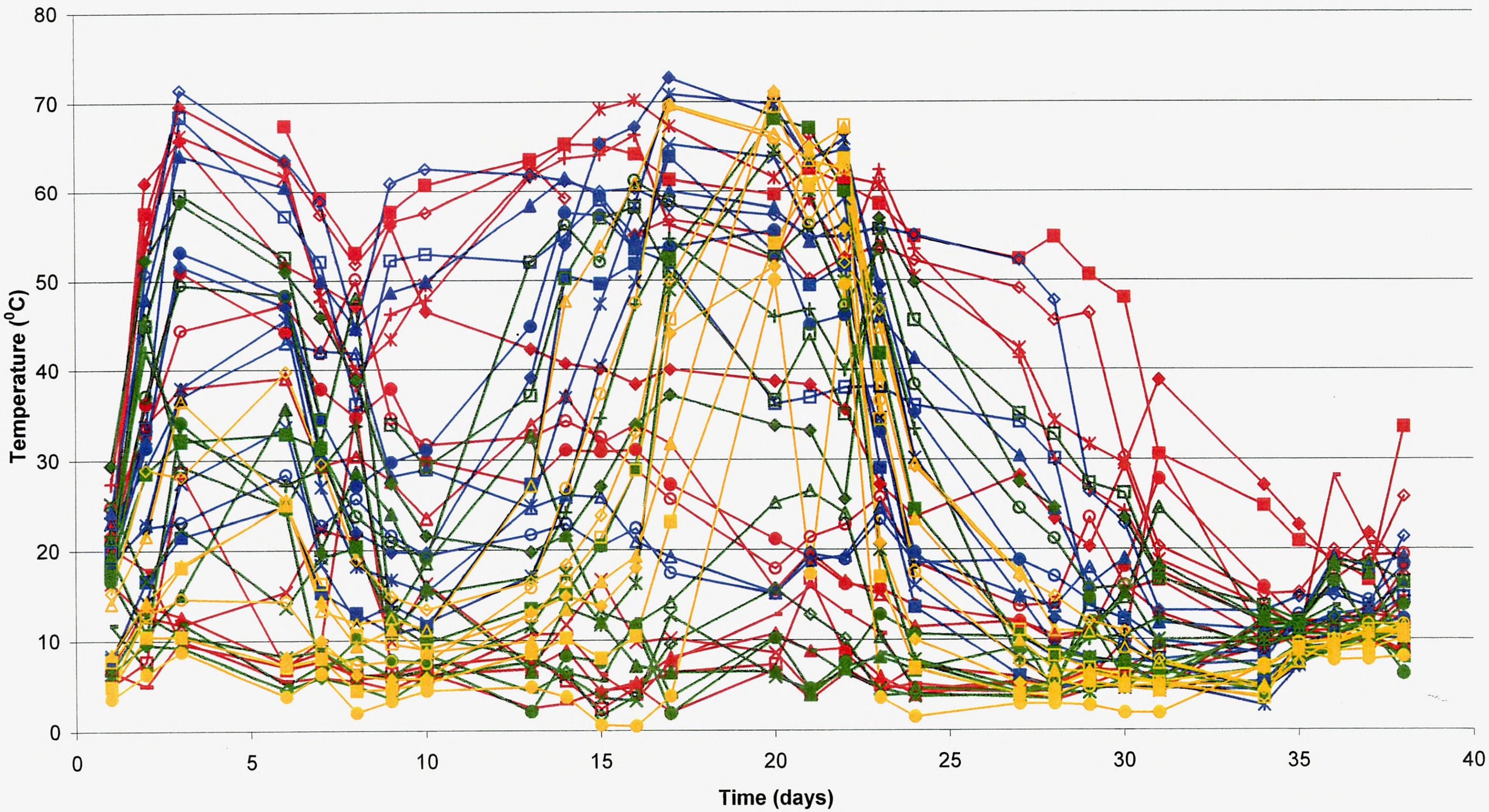




80
70
60
50
40
30
20
10
0
Temperature (^{0}C)
0
5
10
15
20
25
30
35
40
Time (days)

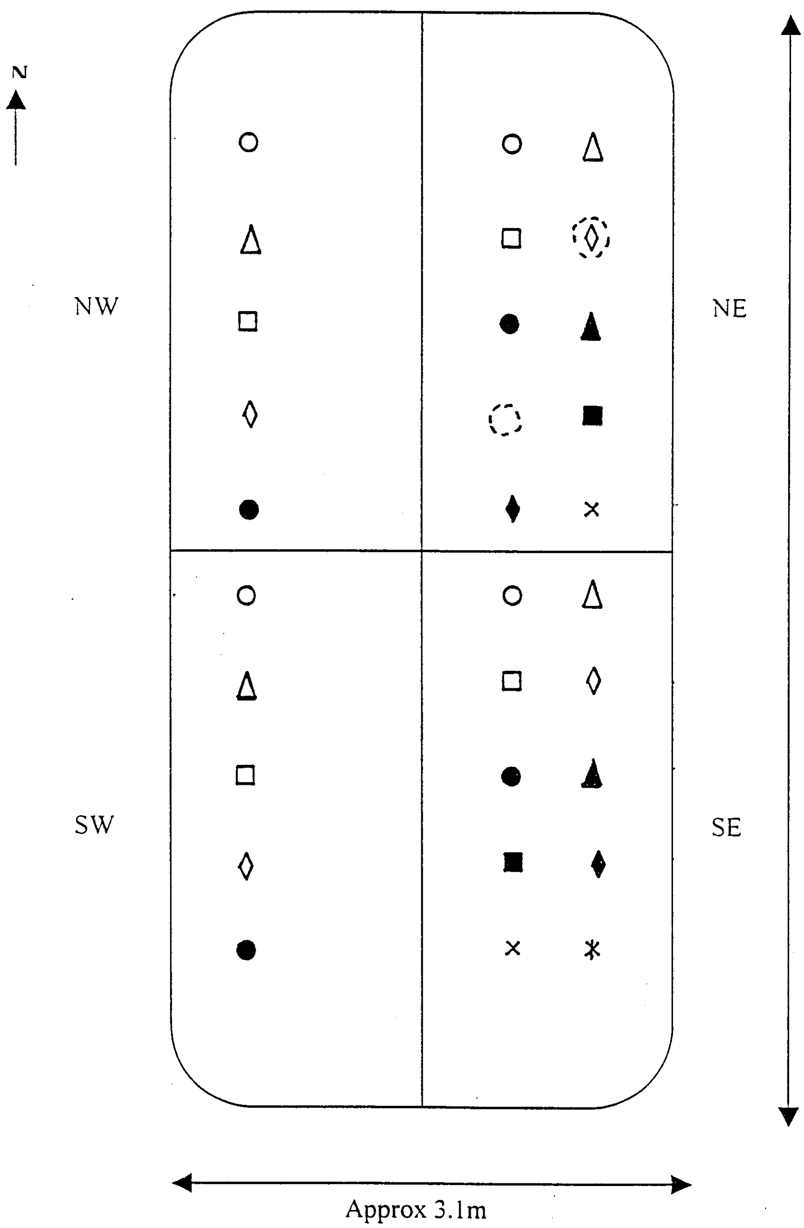
Figure 10: Riverside composting Field Trial 1 (winter) windrow temperatures (°C) Layer 2 (0.5m high) arranged by geographic quarters (NW, NE, SW, SE) over Days 1 to 38. Temperature trends from operational thermocouples as described in the diagram below are shown in relationship to their location within the windrow structure (approximate dimensions given (m)). The following colours have been used to represent the windrow regions: Blue (NW), Red (NE), Yellow (SW), Green (SE).
NW quarter thermocouples (with depth shown) (○ 0.5m) (△1m) (□ 0.5m) (◇ 1m) (● 0.5m) (▲ 1m) (■ 0.5m) (◆ 1m) (× 0.5m) (∗ 1m)
NE quarter thermocouples (with depth shown) (○ 2m) (△1m) (□ 0.5m) (◇ 2m) (● 1m) (▲ 0.5m) (■ 2m) (◆ 1m) (× 0.5m) (∗ 2m) (+ 2m) (-1m) (▪ 0.5m)
SW quarter thermocouples (with depth shown) (○ 0.5m) (△1m) (□ 0.5m) (◇ 1m) (● 0.5m) (▲ 1m) (■ 0.5m) (◆ 1m)
SE quarter thermocouples (with depth shown) (○ 2m) (△1m) (□ 1m) (◇ 0.5m) (● 1m) (▲ 0.5m) (■ 2m) (◆ 1m) (× 0.5m) (∗ 2m) (+ 1m) (-0.5m)
◌ Indicates thermocouples yielding partial data sets

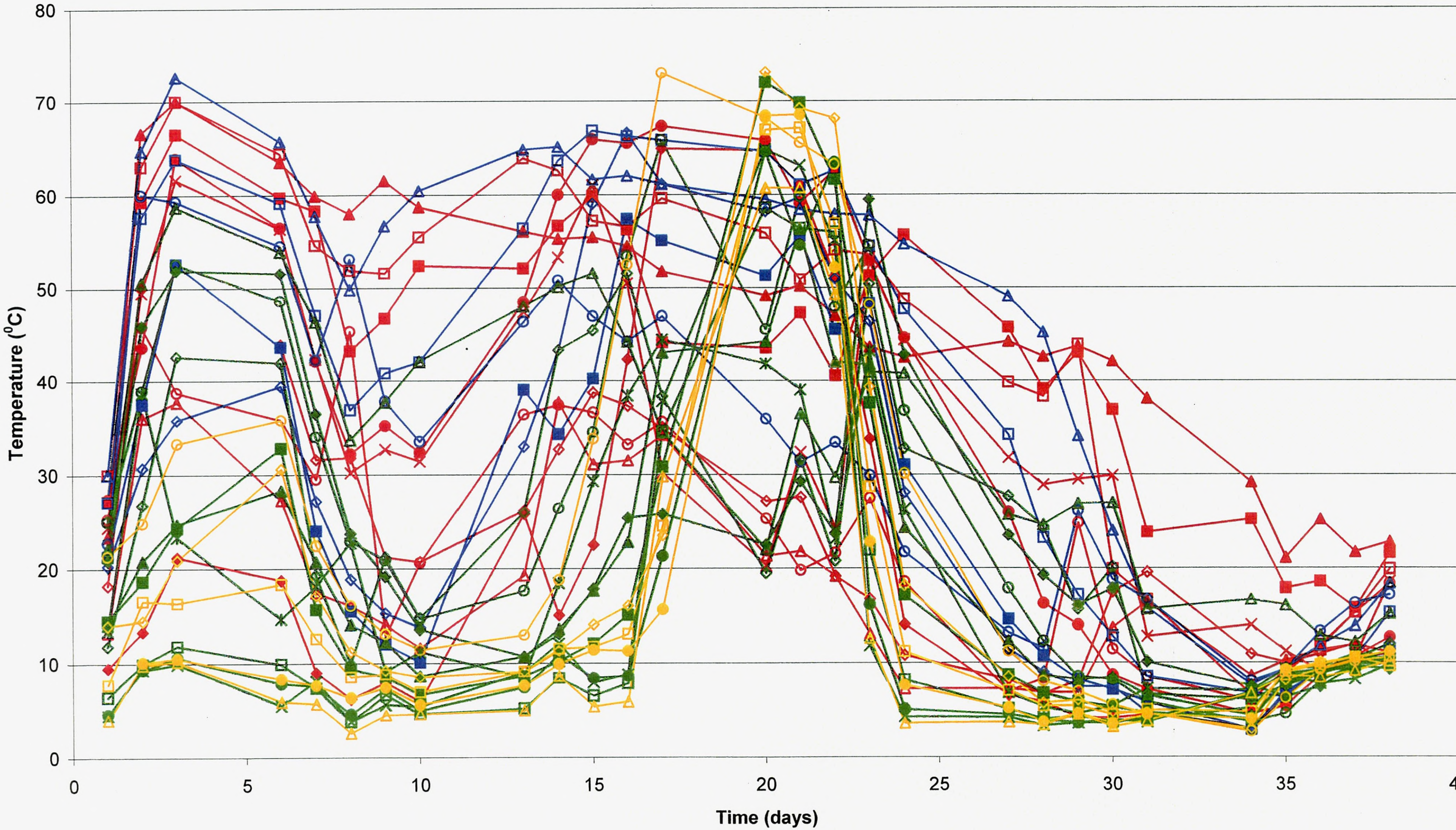




80
70
60
50
40
30
20
10
0
Temperature (°C)
0
5
10
15
20
25
30
35
40
Time (days)

Figure 11: Riverside composting Field Trial 1 (winter) windrow temperatures (°C) Layer 3 (1m high) arranged by geographic quarters (NW, NE, SW, SE) over Days 1 to 38. Temperature trends from operational thermocouples as described in the diagram below are shown in relationship to their location within the windrow structure (approximate dimensions given (m)). The following colours have been used to represent the windrow regions: Blue (NW), Red (NE), Yellow (SW), Green (SE).
NW quarter thermocouples (with depth shown) (○ 0.5m) (△0.5m) (□ 0.5m) (◇ 0.5m) (● 0.5m)
NE quarter thermocouples (with depth shown) (○ 1m) (△ 0.5m) (□ 1m) (◇ 0.5m) (● 1m) (▲ 0.5m) (■ 0.5m) (◆ 1m) (× 0.5m)
SW quarter thermocouples (with depth shown) (○ 0.5m) (△ 0.5m) (□ 0.5m) (◇ 0.5m) (● 0.5m)
SE quarter thermocouples (with depth shown) (○ 1m) (△ 0.5m) (□ 1m) (◇ 0.5m) (● 1m) (▲ 0.5m) (■ 1m) (◆ 0.5m) (× 1m) (✳ 0.5m)
( ) Indicates thermocouples yielding partial data sets





80
70
60
50
40
30
20
10
0
Temperature (^{0}C)
0
5
10
15
20
25
30
35
40
Time (days)

Figure 12: Riverside composting Field Trial 1 (winter) windrow temperatures (°C) Layer 4 (1.5m high) arranged by geographic quarters (NW, NE, SW, SE) over Days 1 to 38. Temperature trends from operational thermocouples as described in the diagram below are shown in relationship to their location within the windrow structure (approximate dimensions given (m)). The following colours have been used to represent the windrow regions: Blue (NW), Red (NE), Yellow (SW), Green (SE).

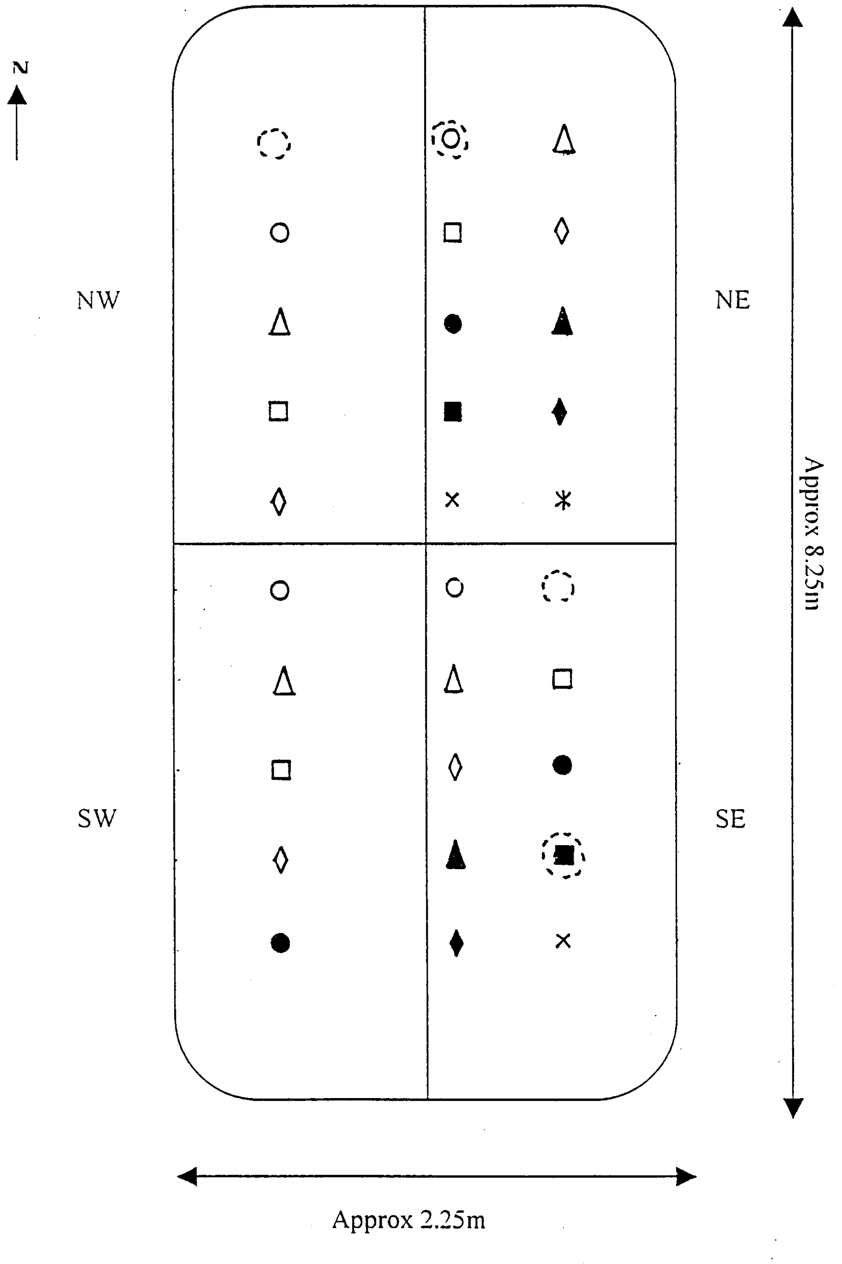
NW quarter thermocouples (with depth shown) (○ 0.5m) (△0.5m) (□ 0.5m) (◇ 0.5m)

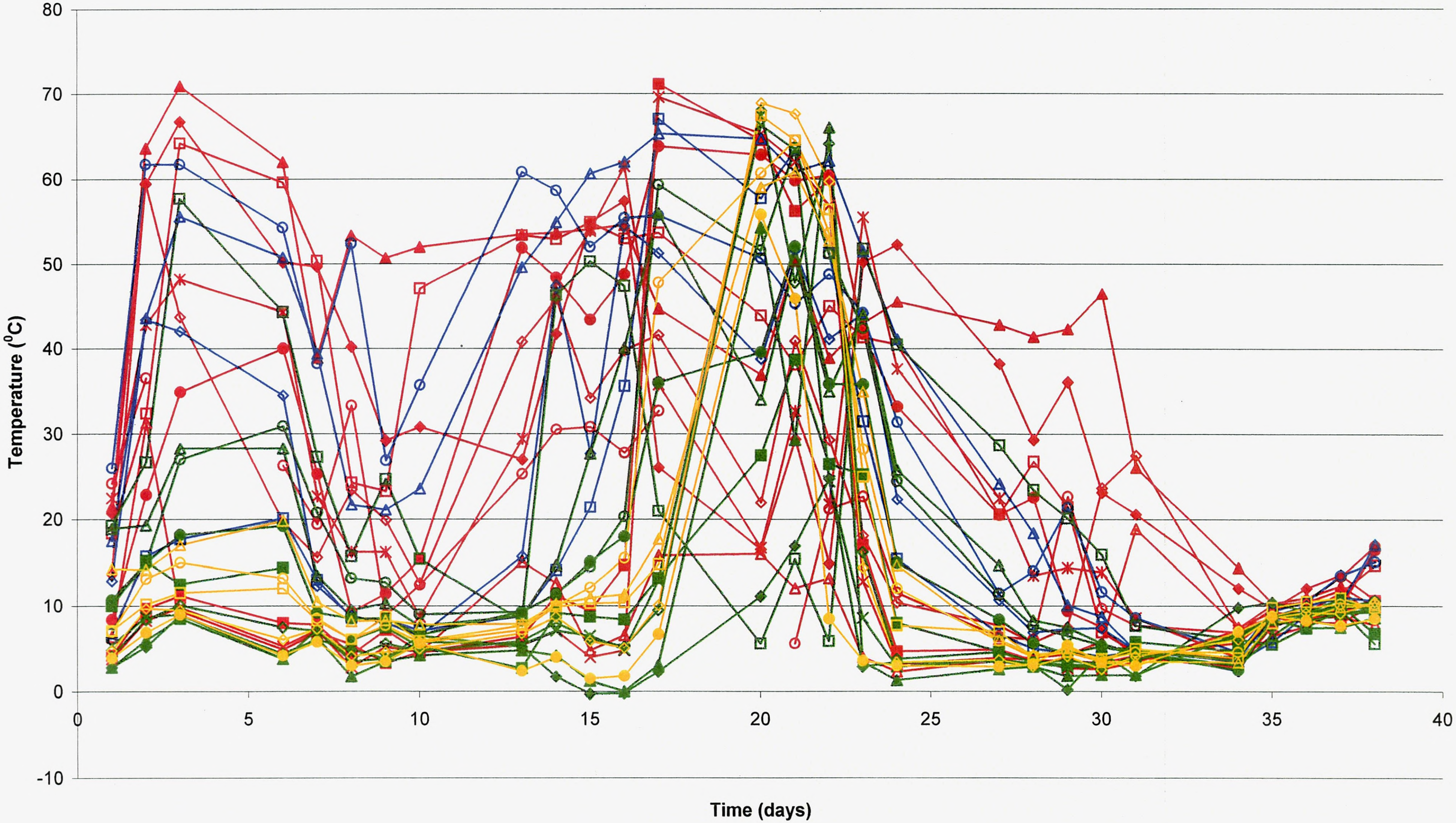
NE quarter thermocouples (with depth shown) (○ 1m) (△ 0.5m) (□ 1m) (◇ 0.5m) (● 1m) (▲ 0.5m) (■ 0.5m) (◆ 1m) (× 1m) (✳ 0.5m)

SW quarter thermocouples (with depth shown) (○ 0.5m) (△ 0.5m) (□ 0.5m) (◇ 0.5m) (● 0.5m)

SE quarter thermocouples (with depth shown) (○ 1m) (△ 1m) (□ 0.5m) (◇ 1m) (● 0.5m) (▲ 1m) (■ 0.5m) (◆ 1m) (× 0.5m)

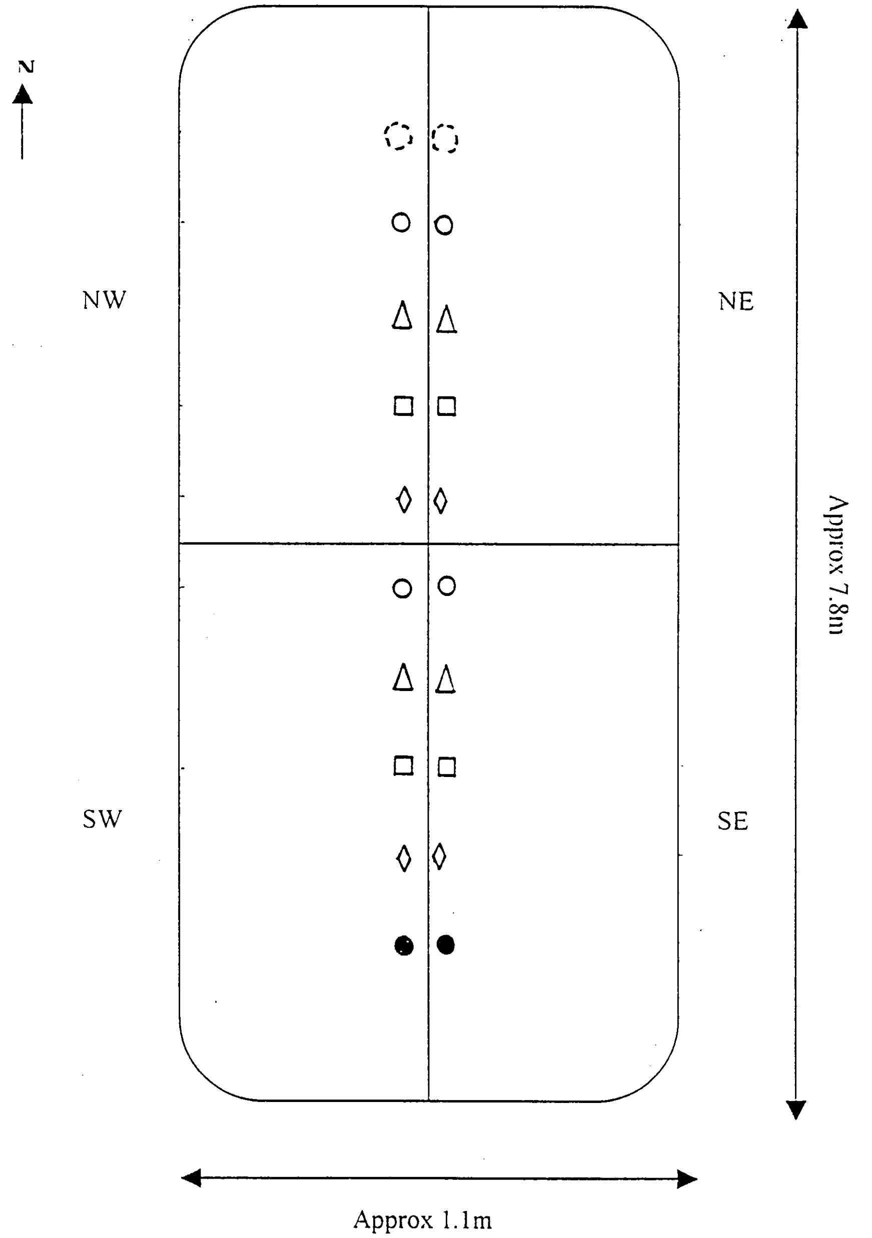
( ) Indicates thermocouples yielding partial data sets

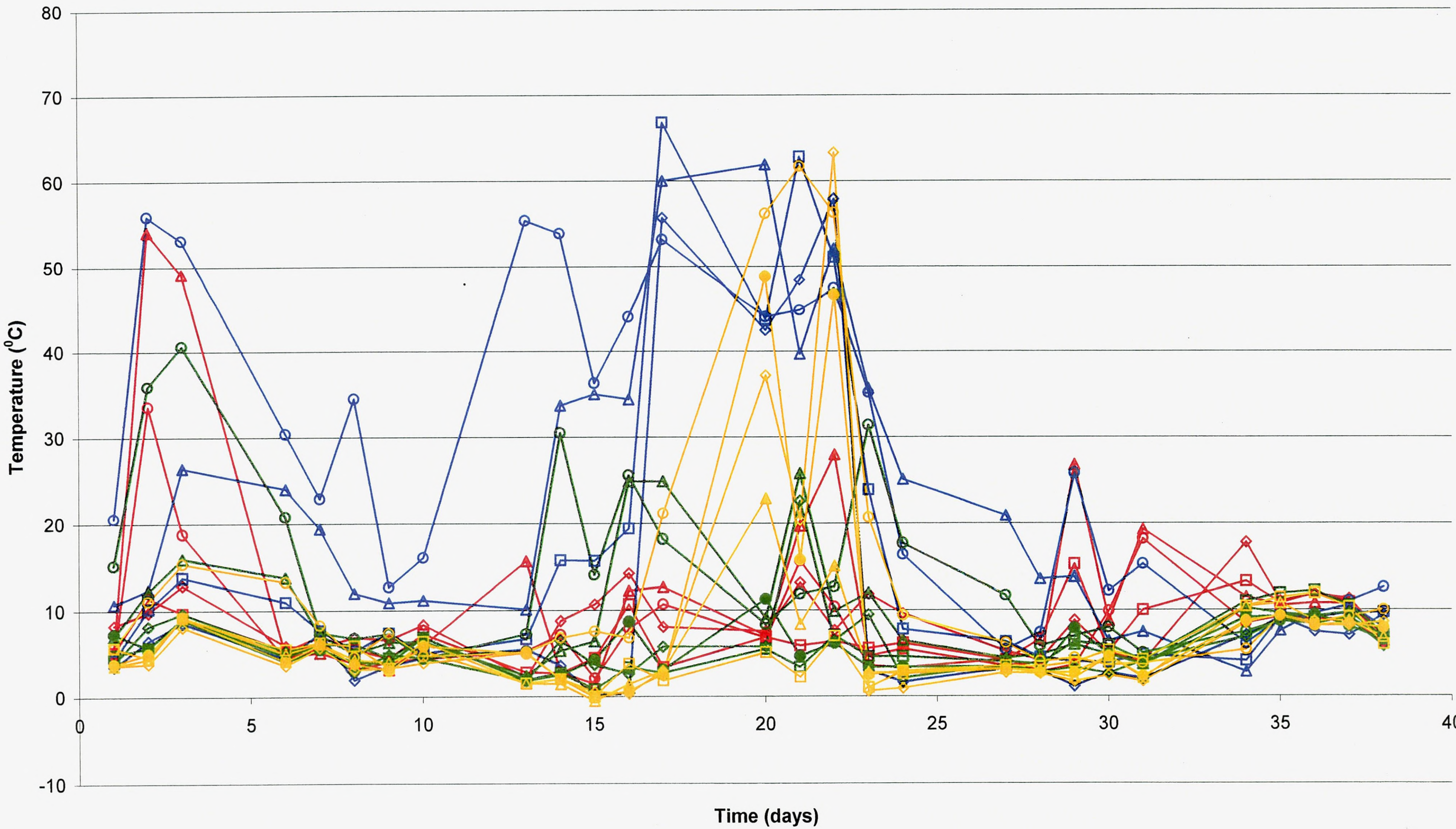




Temperature (^{0}C)
Time (days)
80
70
60
50
40
30
20
10
0
-10
0
5
10
15
20
25
30
35
40

Figure 13: Riverside composting Field Trial 1 (winter) windrow temperatures (°C) Layer 5 (2m high) arranged by geographic quarters (NW, NE, SW, SE) over Days 1 to 38. Temperature trends from operational thermocouples as described in the diagram below are shown in relationship to their location within the windrow structure (approximate dimensions given (m)). The following colours have been used to represent the windrow regions: Blue (NW), Red (NE), Yellow (SW), Green (SE).
NW quarter thermocouples (with depth shown) (○ 0.5m) (△0.5m) (□ 0.5m) (◇ 0.5m)
NE quarter thermocouples (with depth shown) (○ 0.5m) (△ 0.5m) (□ 1m) (◇ 0.5m)
SW quarter thermocouples (with depth shown) (○ 0.5m) (△ 0.5m) (□ 0.5m) (◇ 0.5m) (● 0.5m)
SE quarter thermocouples (with depth shown) (○ 0.5m) (△ 0.5m) (□ 0.5m) (◇ 0.5m) (● 0.5m)
◌ Indicates thermocouples yielding partial data sets





80
70
60
50
40
30
20
10
0
-10
Temperature (0C)
0
5
10
15
20
25
30
35
40
Time (days)

The data related to Field Trial 1 show firstly, the range of temperatures found in different parts of the windrow. In general terms layers 1 to 4 showed remarkably similar spreads of temperature plots. A major feature which is revealed here is that all layers of the windrow exhibited truly thermophilic temperatures, i.e. 50°C to 70°C, and that in layers 1 to 4 many parts of the windrow these temperatures were sustained for extended periods of time, indicating both good potential decomposition rates and pathogen reduction. This was in stark contrast to the temperature profile presented in the overall mean temperature windrow plot (Figure 6). The data presented in Figures 9 to 13 revealed that large volumes of the windrow in all layers (bottom, middle and top) were physically and chemically capable of establishing and sustaining a very active thermophilic microbial population. It is also vital to note that, concurrent to the proliferation of high temperature zones within the windrow, large regions of the structure were at low mesophilic temperatures and even at around the ambient air temperature. These temperatures were not limited to a particular layer of the windrow or time period but were common to all.

TEMPERATURE DATA REVEALS LOCATION BIAS

Figures 9 to 13 indicate an apparent locational bias towards the development of elevated temperatures within the windrow. Parts of the windrow located in the NE and NW quarters showed a faster and more prolonged maintenance of thermophilic temperatures than other parts of the windrow. The SE and SW featured more strongly during the later peak period around day 21, combining with the NE and NW zones to produce the peak observed at this time in the overall mean temperature trend. There was a very rapid rise in temperature in large parts of the SE and SW quadrants (noted by the extreme slope of the plots and bunching of lines) around days 15 to 17, followed by an equally dramatic fall of temperatures in the southern half of the windrow. In many ways it was the temperature readings from the SE and SW which gave the overall temperature plot its characteristic profile (two peaks with a depression in between) and not the northern half of the structure which retained thermophilic temperatures in a more stable fashion. These results demonstrate that the development and distribution of temperature within a windrow is not uniform, even in a given layer of material, and that there are simultaneous hot and cool zones in all layers at all times. This suggests that in field trial 1, the condition of the windrow (both chemically and physically) in the northern half (NE and NW quarters) was more conducive to the rapid growth of thermophilic microorganisms and the maintenance of these conditions to allow heat to be retained within the structure for extended time periods. It is reasonable to infer that thermophilic conditions were primarily established in these regions of the windrow first and that there was in part a flow of heat down the length of the structure, in the sense that the microbial production of heat in one area, would encourage and enhance the growth and metabolism of microorganisms in neighbouring zones, if otherwise conditions were suitable for development. Lynch and Cherry (1996) found that heating began at pile ends and worked towards the centre when investigating passively aerated winter windrows. However, this was linked to increased exposure to sunlight warming the feedstocks in these regions, allowing development of elevated temperatures in otherwise freezing conditions.

The results for layers 3 to 5 (Figures 11 to 13) indicate that after an initial burst of activity by the existing mesophilic community in the SE and SW quarters, there was pronounced decline microbial activity, as shown by the severe depression of temperature (large sections are at ambient). It was over a week before there was a clear increase in temperatures. Such a situation could possibly have occurred because of the random location of a large volume of less biodegradable materials at this part of the windrow, resulting in retardation of thermophilic composting. However, although possible in part, the rapid simultaneous decline of high temperatures in all parts of the windrow suggested other factors could have played a part. Delayed development of thermophilic composting (*via* low nutrient availability) would result in the eventual production of a similar temperature pattern to NE and NW zones, but simply shifted along the time axis and this was not the case. It could be argued that a relatively open structure such as that given by a mass of woody material would have poor heat retaining characteristics. However, this was unlikely to have existed in all layers of the windrow, especially the lower ones. Additionally, there was no evidence on observation that any part of the experimental windrow was characteristically different in nature either during construction or after establishment.

INFLUENCE OF CLIMATOLOGICAL FACTORS

The data for Field Trial 1 (Figures 9 to 13) clearly shows a marked difference between the NE and NW quarters of the windrow and the SE and SW quarters in terms of temperature development and trends. These have been reviewed above with possible effecting factors. However, there is one factor which has not as yet been considered and this is the weather. Figures 14 and 15 show the mean windspeed (MPH) and prevailing direction over the period of the trial. The mean windspeed plot shows three main features, two periods of increased windspeed, at the beginning and end of the time period, and an interval of decreased windspeed in between. The graph displaying wind directional data clearly shows the majority of wind coming from a WSW direction during the trial. These pieces of data are vital to understanding the behaviour as regards temperature of the SE and SW quarters of the windrow. The Riverside composting site is a particularly exposed location, with the wide estuary (3 to 5 miles of open water) of the River Tay providing its southeastern, southern and southwestern perimeters. There are no trees or other windbreaks and the land, being reclaimed as landfill from the river, is essentially flat. The SE and SW quarters of the windrow represent the most exposed areas of the structure, whilst the NE and NW quarter, being of the slightly more sheltered landward area, with other windrows and some trees present to break the wind.

Figure 14: Riverside composting Field Trial 1 (winter). Mean windspeed in Miles Per Hour (MPH) over Days 1 to 38 of trial. Windspeed data was derived from information provided by the Dundee Airport weather station (National Weather Service, Internet Weather Source, Current Weather Conditions – Dundee / Riverside, United Kingdom: http://weather.noaa.gov/weather/current/EGPN.html) adjacent to the composting site.

(○) Mean windspeed (MPH)

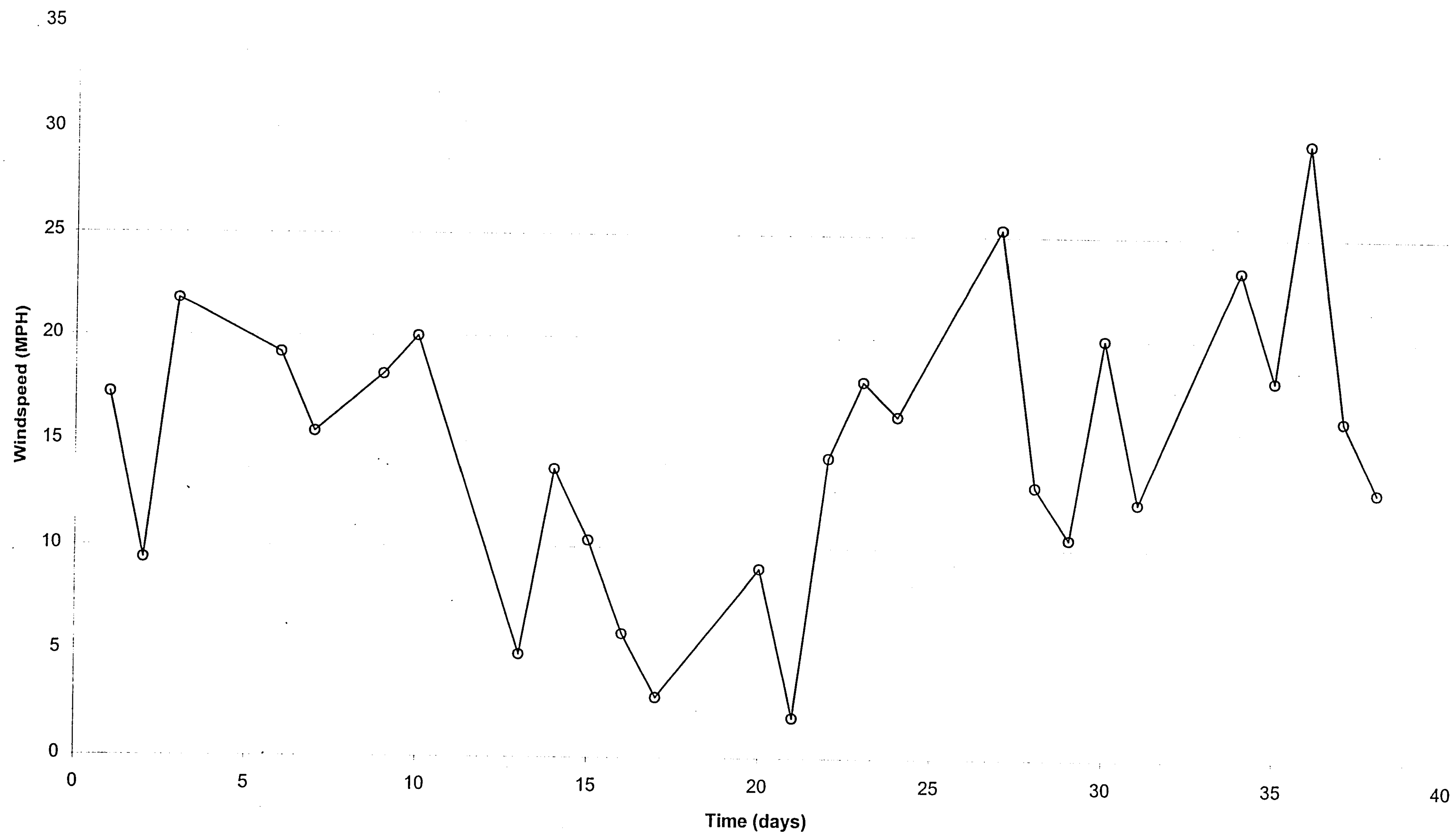
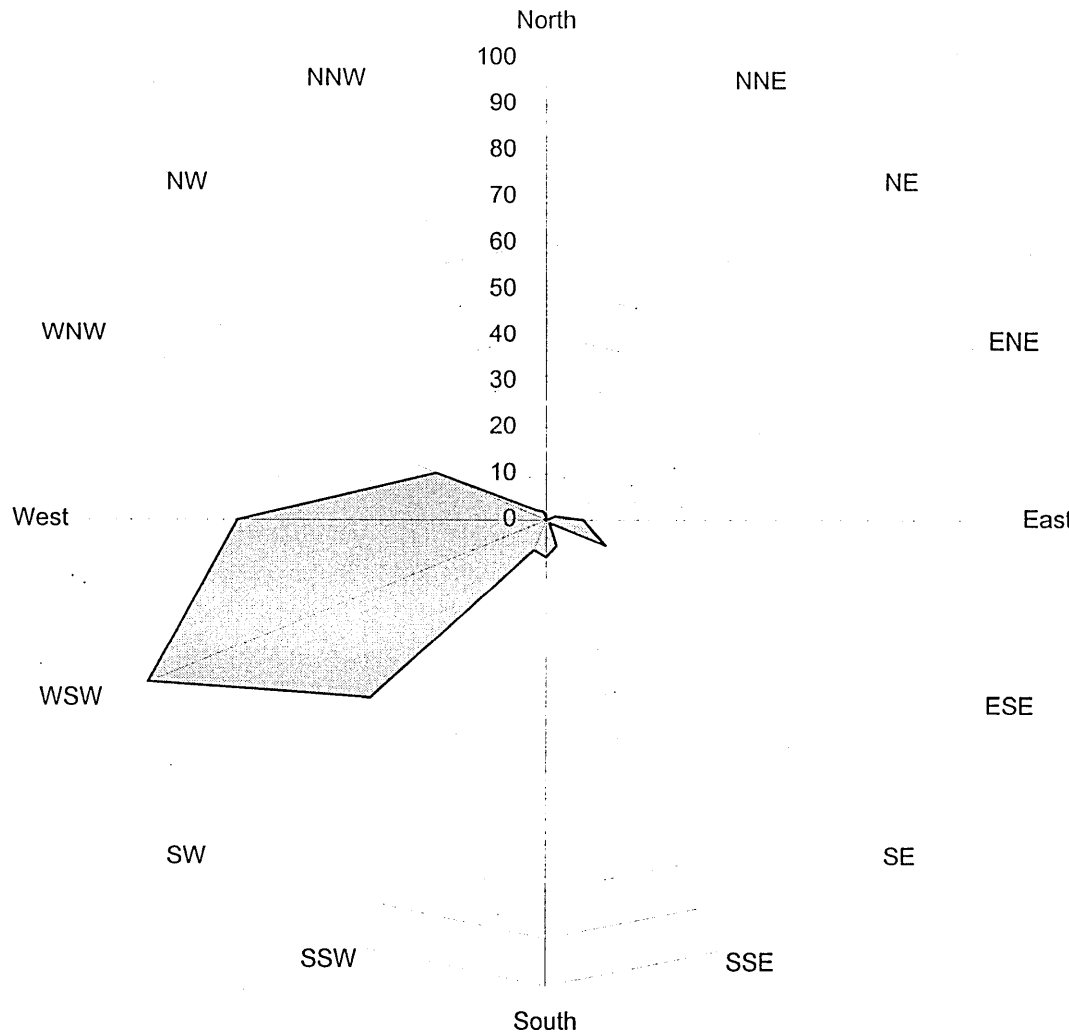

35
30
25
20
15
10
5
0
Windspeed (MPH)
0
5
10
15
20
25
30
35
40
Time (days)

Figure 15: Riverside composting Field Trial 1 (winter). Collected wind directional data, (shaded area represents the number of readings per coordinate) showing prevailing directional trend over Days 1 to 38 of field trial. Derived from information provided by the Dundee Airport weather station (National Weather Service, Internet Weather Source, Current Weather Conditions – Dundee / Riverside, United Kingdom: http://weather.noaa.gov/weather/current/EGPN.html) adjacent to the composting site.


North
NNE
NE
ENE
East
ESE
SE
SSE
South
SSW
SW
WSW
West
WNW
NW
NNW
100
90
80
70
60
50
40
30
20
10
0

It is proposed that the external major factor affecting the development of windrow temperatures was the wind. The most exposed parts of the windrow in terms of wind direction were the parts that exhibited the slower development of and shorter retaining of thermophilic temperatures, in all layers and depths of the experimental windrow. Although physical, chemical and structural factors would also have potentially contributed to these conditions, the clear divide in temperature behaviour between each end of windrow could not be explained using these factors alone. It is reasoned that the wind provided a negative influence on the development of elevated temperatures within the SE and SW quarters of the windrow. Higher windspeeds during the first ten days of the trial, seemed to have depressed the development of thermophilic temperatures in many parts of this region of the windrow, especially layers 3 to 5. Although there was an initial burst of mesophilically derived heat, the coupling of the increased windspeed predominately from a south-westerly direction and the natural windrow tendency for slightly depressed microbial activity during the first succession period, resulted in the prolonged retardation of thermophilic conditions. It was only after a period of calmer conditions that it was possible for these regions of the windrows to establish thermophilic temperatures. The increasing windspeeds during the latter stages of the trial again seemed to negatively affect the sustainability of these high temperature environments and this could be coupled with the general decline in probable physical and chemical conditions (as indicated by the windrow-wide decline in temperatures), such as slumping causing over-compaction resulting in poor gas exchange, and reduced levels of available nutrients. The ambient temperature, which was essentially constant (low) throughout the trial, would have affected all regions of the windrow (NE, NW, SE and SW), and because there were clearly large zones of prolonged thermophilic temperatures within the structure, there is no reason to suggest that low ambient temperatures could prevent the development of high temperatures in particular regions of the windrow (SE and SW), which do not only represent zones such as the extremities of the structure (which could more clearly be directly affected by ambient temperature trends), but internal areas too. However, increased windspeeds, particularly repeatedly from the same direction, could affect the propagation and retention of high temperatures within a windrow. This effect was lessened within areas of the structure of greatest cross section as seen in layers 1 and 2, but was still capable of inducing poor performance into the composting operation.

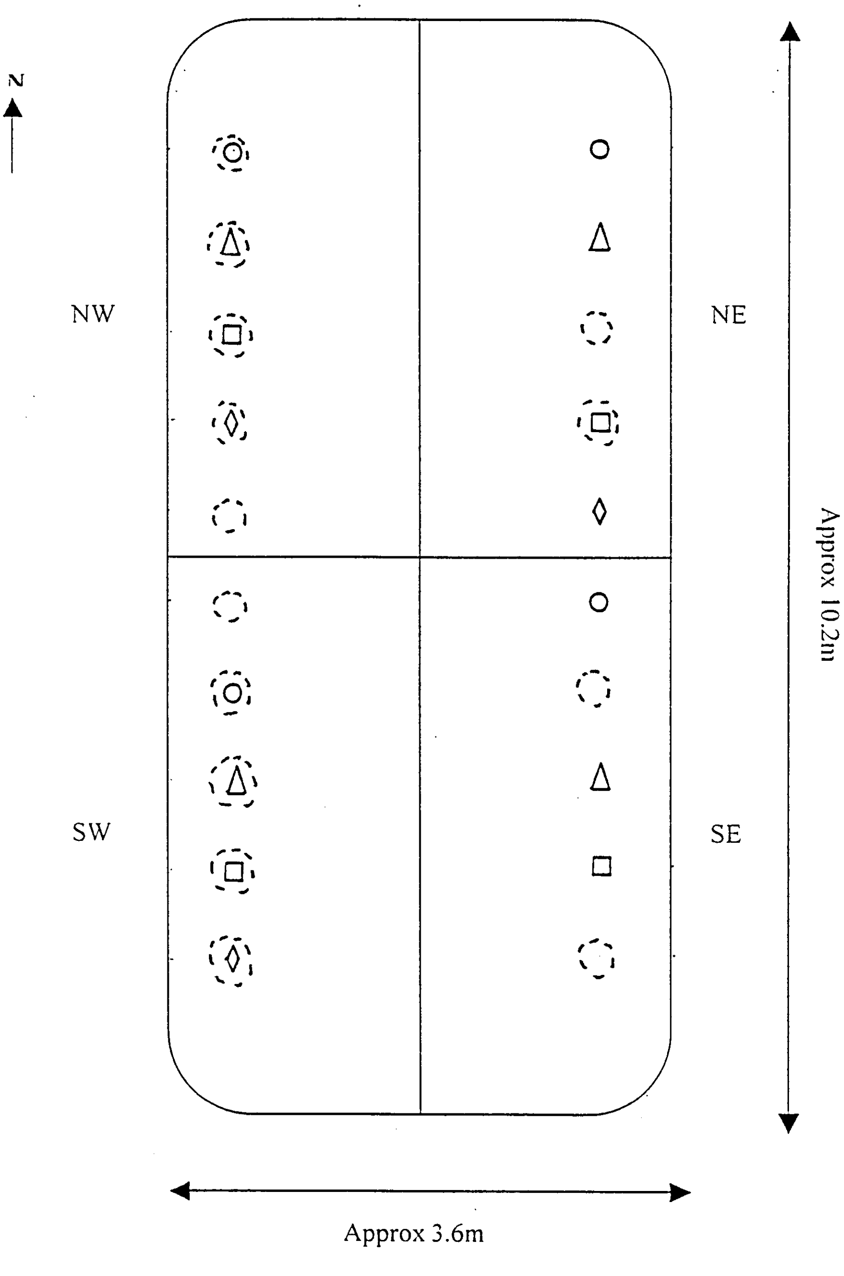
FIELD TRIAL 2: ANALYSIS OF TEMPERATURE BY WINDROW QUARTER (NE, SE, NW, SW) AND BY DEPTH OF THERMOCOUPLE

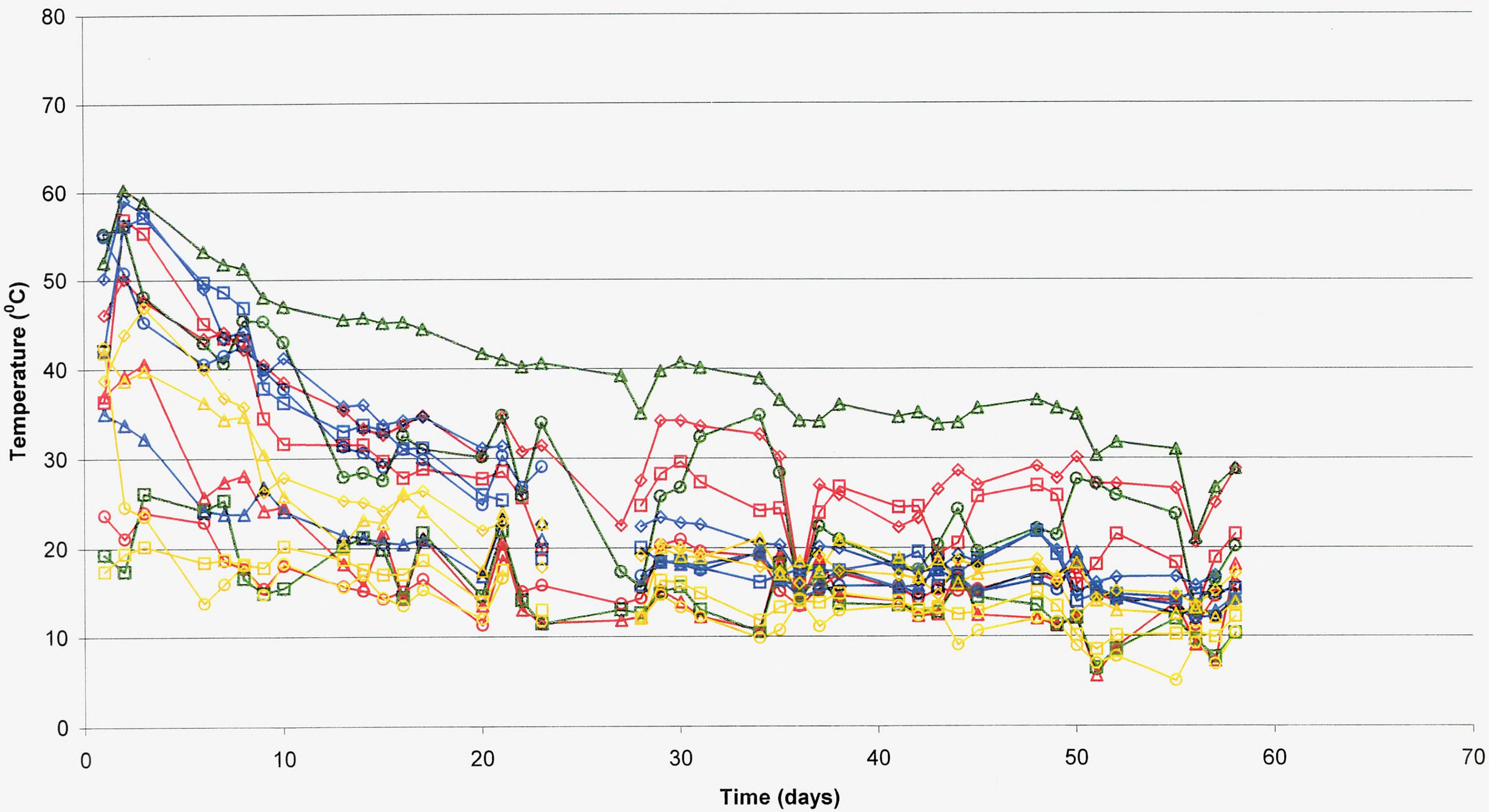
Figures 16 to 22, show the temperature trends (day 1 to 58) for the Field Trial 2 experimental windrow arranged by quadrants (as above) and by depth of thermocouple for each of the three layers (Layer 1 0.3m high; 0.5m, 1m and 1.5m deep, Layer 2 0.75m high; 0.5m & 1m deep and Layer 3 1m high; 0.5m & 1m deep) of probes placed within the structure. Details of thermocouple arrangements are presented with Figures 16 to 22.

The data reveals that there was a wide spread of temperatures within the structure, with prolonged periods of thermophilic activity, within the 65°C to 75°C range. This trial in general exhibited higher temperatures than the winter trial. The general reason for this was the more diverse and higher quality feedstocks typically available for composting during the summer months. However, in a similar fashion to Field Trial 1 all layers displayed temperatures in both the mesophilic and thermophilic ranges simultaneously and at all time periods of the trial. This reinforces the concept that temperature development and maintenance within a windrow is not uniform even at similar locations inside the structure.

Unlike Field Trial 1, there was no particular temperature bias dependant on physical location, (i.e. NE, SE, SW, and NW). Figure 23 shows that prevailing wind direction was split evenly between easterly and westerly directions during the trial. This would suggest that no one area of the windrow was unilaterally exposed to the wind, (i.e. wind derived temperature effects would be more uniformly distributed). Windspeed throughout large parts of the trial was low, with only a few major peaks (Figure 24).

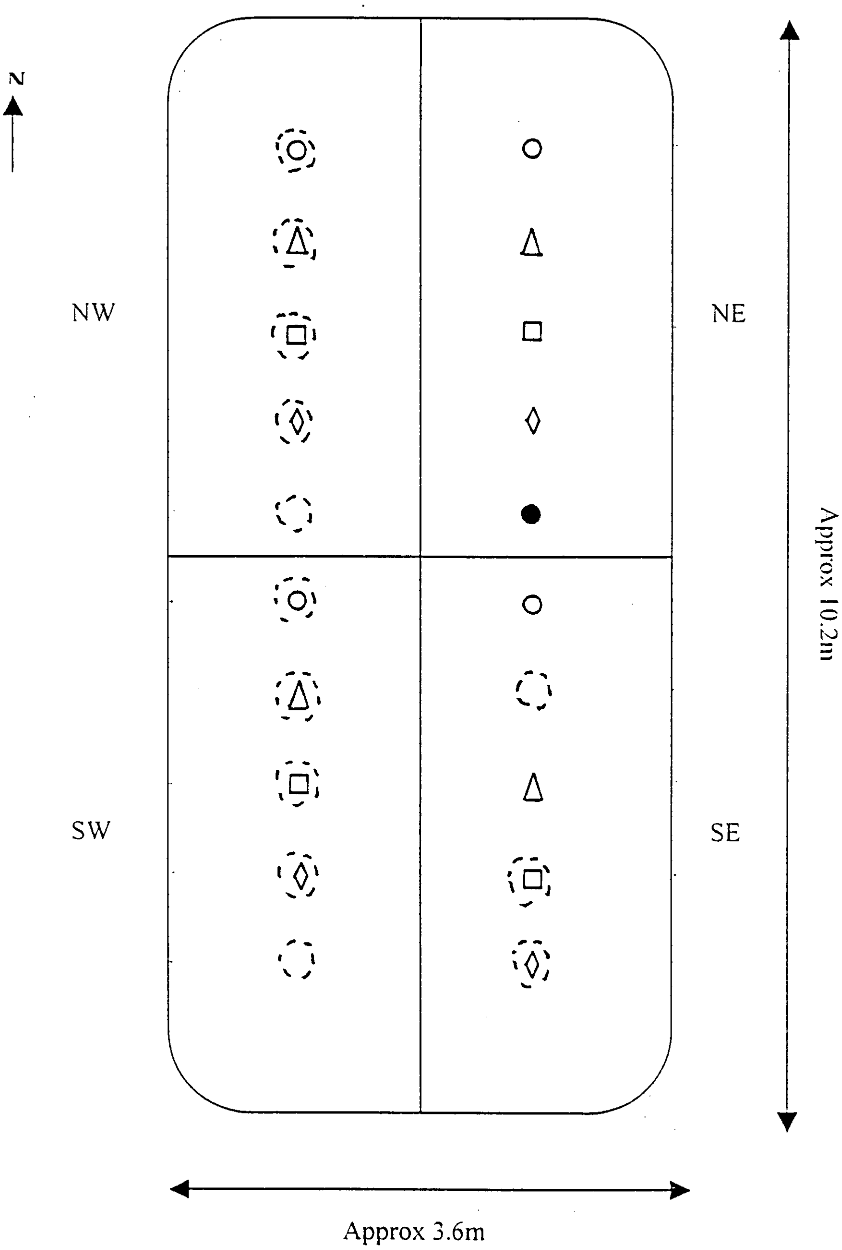
Figure 16: Riverside composting Field Trial 2 (summer) windrow temperatures (°C) Layer 1 (0.3m high, 0.5m deep) arranged by geographic quarters (NW, NE, SW, SE) over Days 1 to 58. Temperature trends from operational thermocouples as described in the diagram below are shown in relationship to their location within the windrow structure (approximate dimensions given (m)). Discontinuous data plots indicate brief periods of datalogging equipment failure. The following colours have been used to represent the windrow regions: Blue (NW), Red (NE), Yellow (SW), Green (SE).
NW quarter thermocouples (with depth shown) (○ 0.5m) (△0.5m) (□ 0.5m) (◇ 0.5m)
NE quarter thermocouples (with depth shown) (○ 0.5m) (△ 0.5m) (□ 0.5m) (◇ 0.5m)
SW quarter thermocouples (with depth shown) (○ 0.5m) (△ 0.5m) (□ 0.5m) (◇ 0.5m)
SE quarter thermocouples (with depth shown) (○ 0.5m) (△ 0.5m) (□ 0.5m)
Indicates thermocouples yielding partial data sets

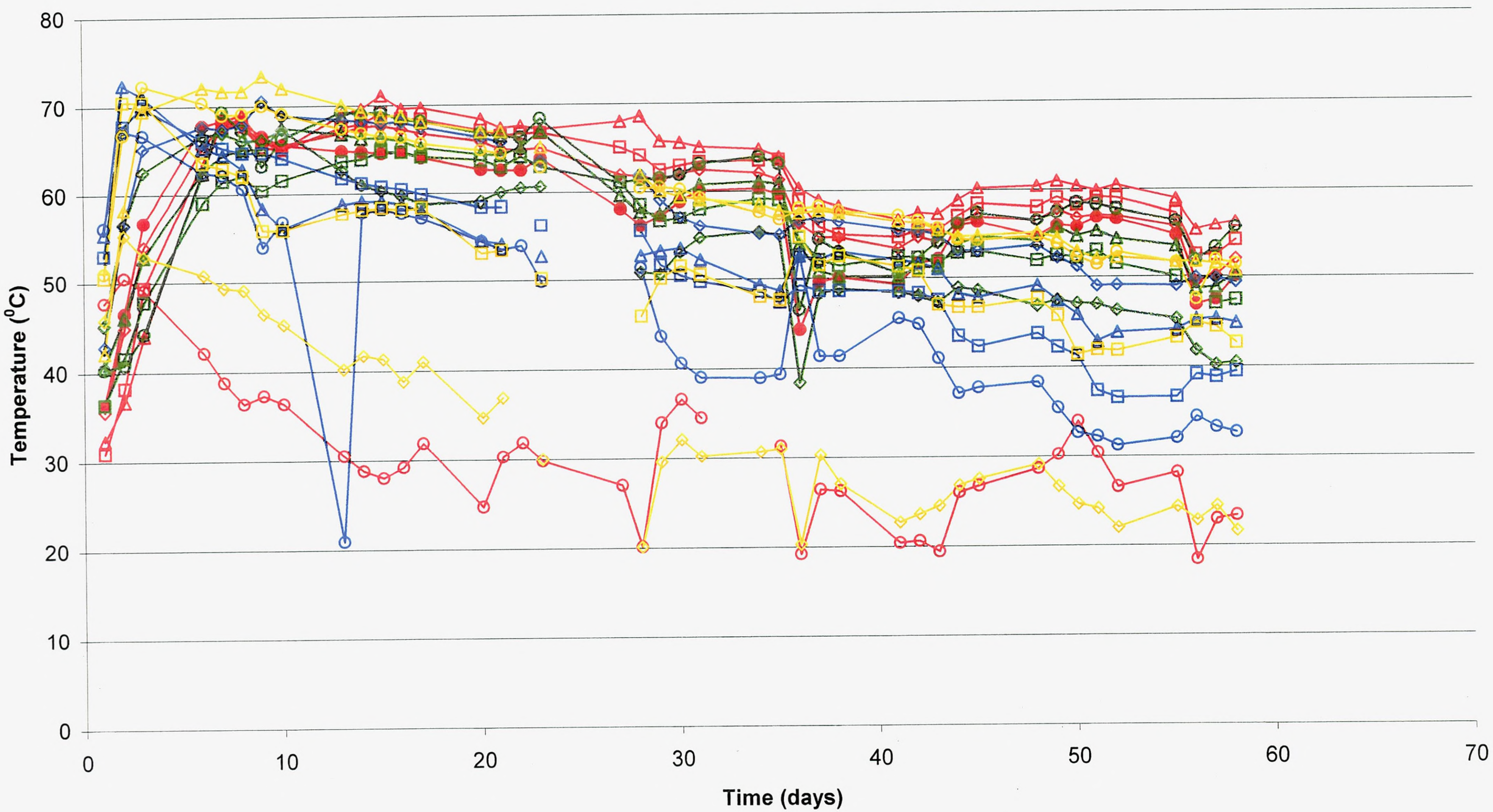




80
70
60
50
40
30
20
10
0
Temperature (^{0}C)
0
10
20
30
40
50
60
70
Time (days)

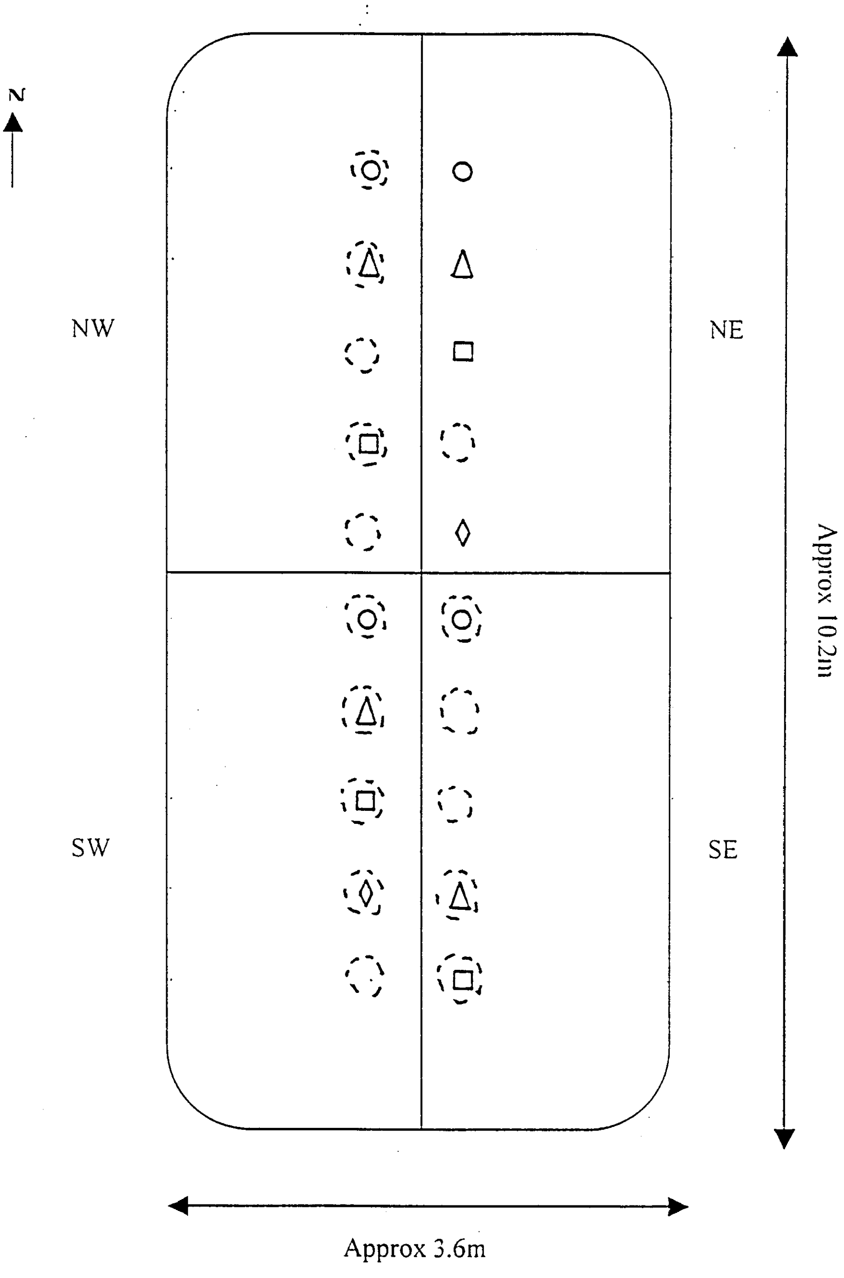
Figure 17: Riverside composting Field Trial 2 (summer) windrow temperatures (°C) Layer 1 (0.3m high and 1m deep) arranged by geographic quarters (NW, NE, SW, SE) over Days 1 to 58. Temperature trends from operational thermocouples as described in the diagram below are shown in relationship to their location within the windrow structure (approximate dimensions given (m)). Discontinuous data plots indicate brief periods of datalogging equipment failure. The following colours have been used to represent the windrow regions: Blue (NW), Red (NE), Yellow (SW), Green (SE).
NW quarter thermocouples (with depth shown) (○ 1m) (△ 1m) (□ 1m) (◇ 1m)
NE quarter thermocouples (with depth shown) (○ 1m) (△ 1m) (□ 1m) (◇ 1m) (● 1m)
SW quarter thermocouples (with depth shown) (○ 1m) (△ 1m) (□ 1m) (◇ 1m)
SE quarter thermocouples (with depth shown) (○ 1m) (△ 1m) (□ 1m) (◇ 1m)
( ) Indicates thermocouples yielding partial data sets

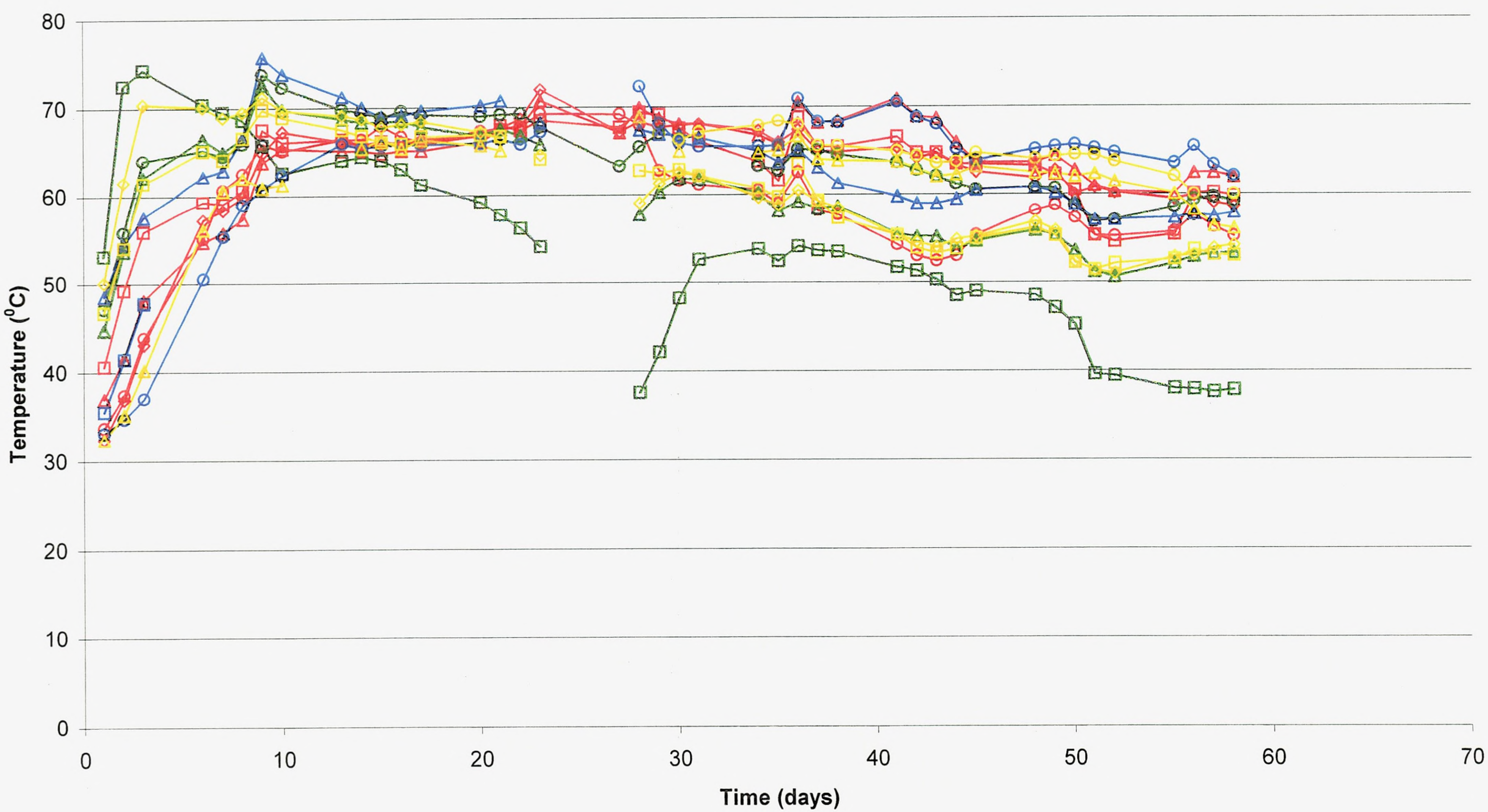




Temperature (°C)
Time (days)
80
70
60
50
40
30
20
10
0
0
10
20
30
40
50
60
70

Figure 18: Riverside composting Field Trial 2 (summer) windrow temperatures (°C) Layer 1 (0.3m high and 1.5m deep) arranged by geographic quarters (NW, NE, SW, SE) over Days 1 to 58. Temperature trends from operational thermocouples as described in the diagram below are shown in relationship to their location within the windrow structure (approximate dimensions given (m)). Discontinuous data plots indicate brief periods of datalogging equipment failure. The following colours have been used to represent the windrow regions: Blue (NW), Red (NE), Yellow (SW), Green (SE).
NW quarter thermocouples (with depth shown) (O 1.5m) (△ 1.5m) (□ 1.5m)
NE quarter thermocouples (with depth shown) (O 1.5m) (△ 1.5m) (□ 1.5m) (◇ 1.5m)
SW quarter thermocouples (with depth shown) (O 1.5m) (△ 1.5m) (□ 1.5m) (◇ 1.5m)
SE quarter thermocouples (with depth shown) (O 1.5m) (△ 1.5m) (□ 1.5m)
( ) Indicates thermocouples yielding partial data sets



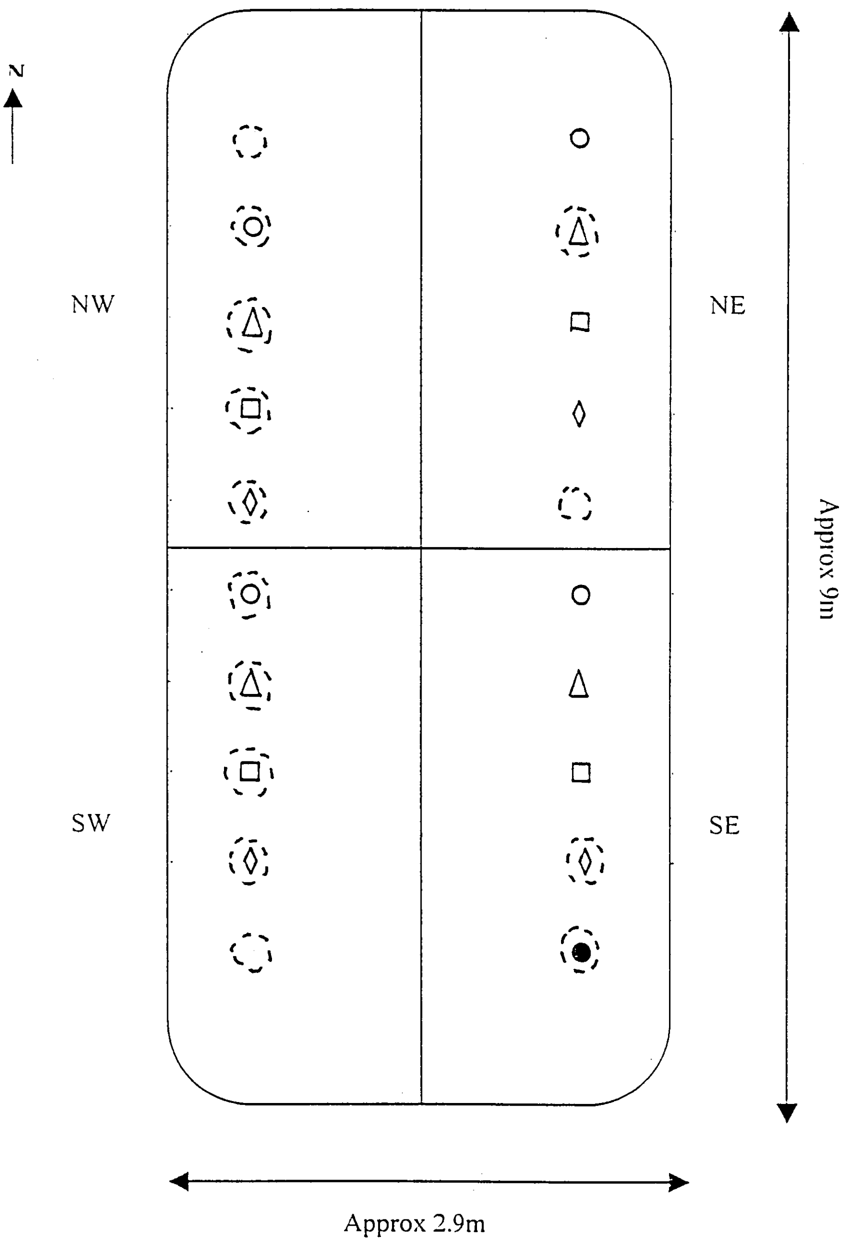


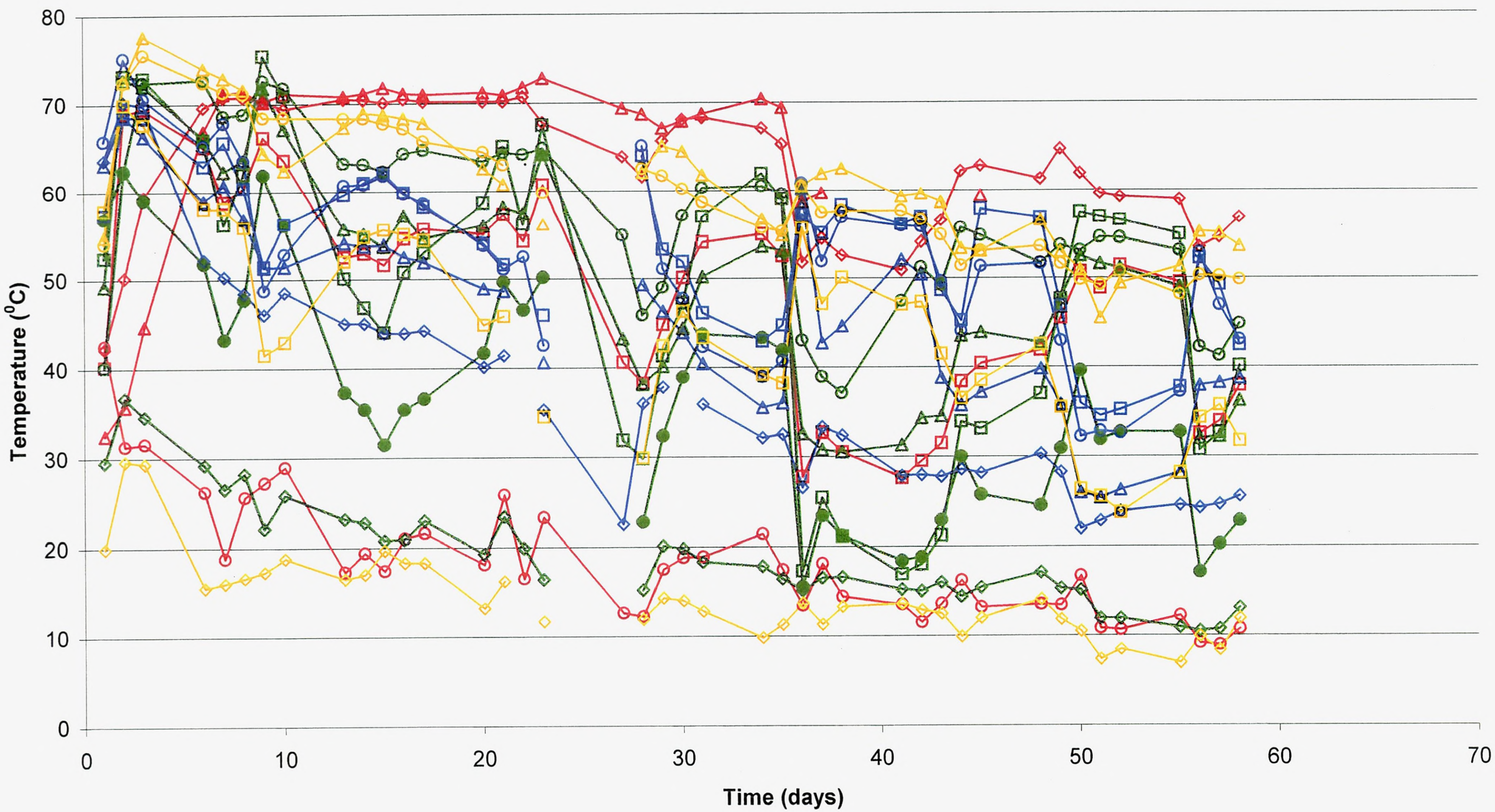
80
70
60
50
40
30
20
10
0
Temperature (^{0}C)
0
10
20
30
40
50
60
70
Time (days)

Figure 19: Riverside composting Field Trial 2 (summer) windrow temperatures (°C) Layer 2 (0.75m high and 0.5m deep) arranged by geographic quarters (NW, NE, SW, SE) over Days 1 to 58. Temperature trends from operational thermocouples as described in the diagram below are shown in relationship to their location within the windrow structure (approximate dimensions given (m)). Discontinuous data plots indicate brief periods of datalogging equipment failure. The following colours have been used to represent the windrow regions: Blue (NW), Red (NE), Yellow (SW), Green (SE).

NW quarter thermocouples (with depth shown) (O 0.5m) (△ 0.5m) (□ 0.5m) (◇ 0.5m)
NE quarter thermocouples (with depth shown) (O 0.5m) (△ 0.5m) (□ 0.5m) (◇ 0.5m)
SW quarter thermocouples (with depth shown) (O 0.5m) (△ 0.5m) (□ 0.5m) (◇ 0.5m)
SE quarter thermocouples (with depth shown) (O 0.5m) (△ 0.5m) (□ 0.5m) (◇ 0.5m) (● 0.5m)

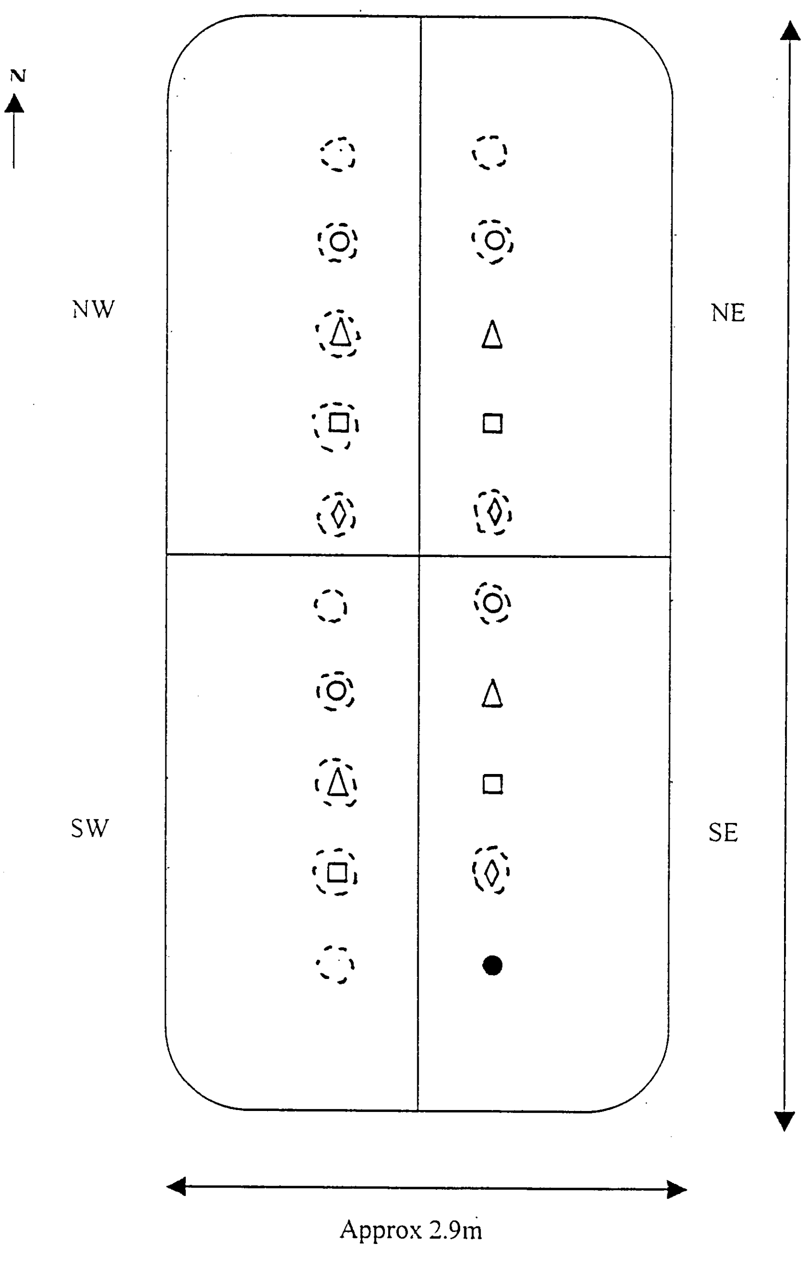
( ) Indicates thermocouples yielding partial data sets

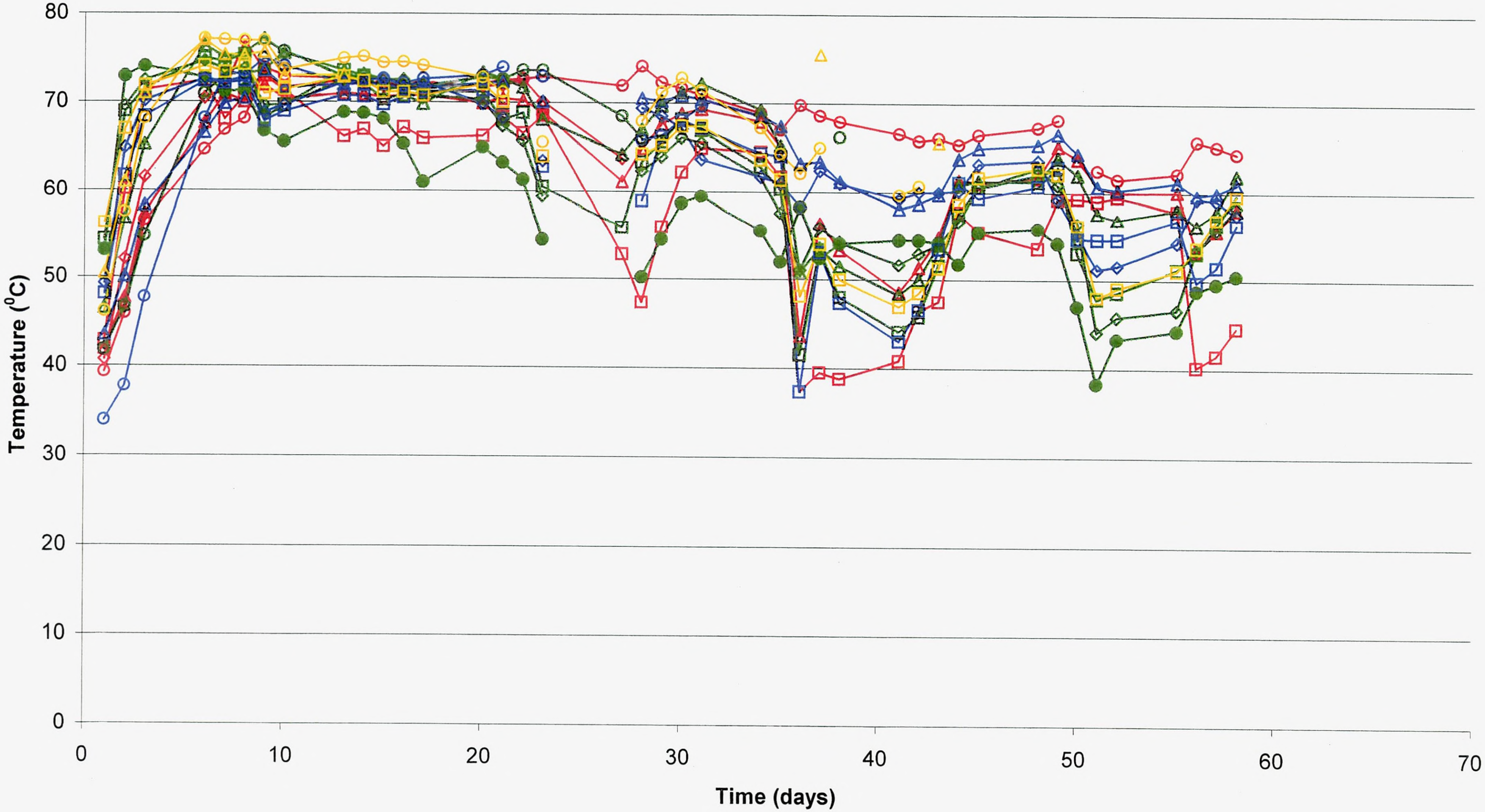




Temperature (^{0}C)
80
70
60
50
40
30
20
10
0
0
10
20
30
40
50
60
70
Time (days)

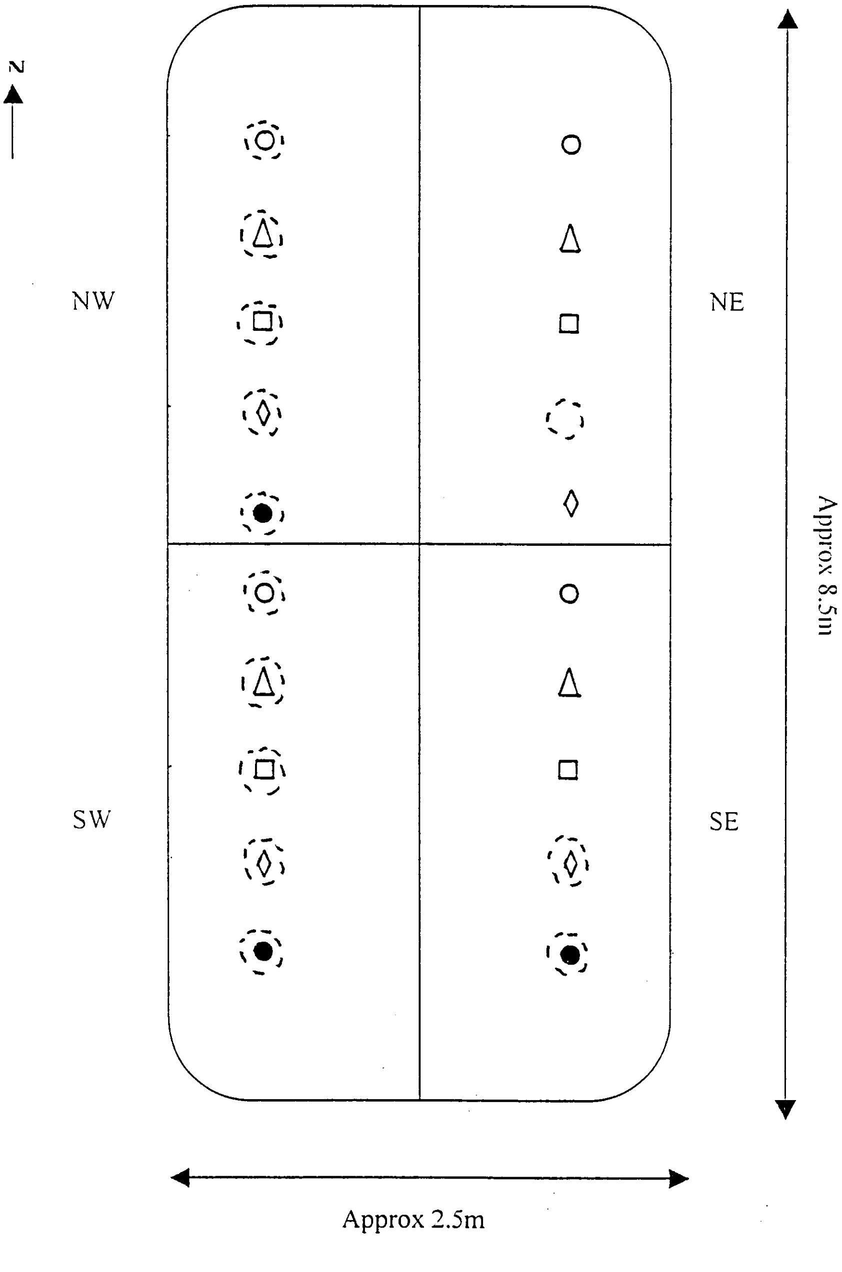
Figure 20: Riverside composting Field Trial 2 (summer) windrow temperatures (°C) Layer 2 (0.75m high and 1m deep) arranged by geographic quarters (NW, NE, SW, SE) over Days 1 to 58. Temperature trends from operational thermocouples as described in the diagram below are shown in relationship to their location within the windrow structure (approximate dimensions given (m)). Discontinuous data plots indicate brief periods of datalogging equipment failure. The following colours have been used to represent the windrow regions: Blue (NW), Red (NE), Yellow (SW), Green (SE).
NW quarter thermocouples (with depth shown) (○ 1m) (△ 1m) (□ 1m) (◇ 1m)
NE quarter thermocouples (with depth shown) (○ 1m) (△ 1m) (□ 1m) (◇ 1m)
SW quarter thermocouples (with depth shown) (○ 1m) (△ 1m) (□ 1m)
SE quarter thermocouples (with depth shown) (○ 1m) (△ 1m) (□ 1m) (◇ 1m) (● 1m)
( ) Indicates thermocouples yielding partial data sets





80
70
60
50
40
30
20
10
0
Temperature (^{0}C)
0
10
20
30
40
50
60
70
Time (days)

Figure 21: Riverside composting Field Trial 2 (summer) windrow temperatures (°C) Layer 3 (1m high and 0.5m deep) arranged by geographic quarters (NW, NE, SW, SE) over Days 1 to 58. Temperature trends from operational thermocouples as described in the diagram below are shown in relationship to their location within the windrow structure (approximate dimensions given (m)). Discontinuous data plots indicate brief periods of datalogging equipment failure. The following colours have been used to represent the windrow regions: Blue (NW), Red (NE), Yellow (SW), Green (SE).
NW quarter thermocouples (with depth shown) (○ 0.5m) (△ 0.5m) (□ 0.5m) (◇ 0.5m) (● 0.5m)
NE quarter thermocouples (with depth shown) (○ 0.5m) (△ 0.5m) (□ 0.5m) (◇ 0.5m)
SW quarter thermocouples (with depth shown) (○ 0.5m) (△ 0.5m) (□ 0.5m) (◇ 0.5m) (● 0.5m)
SE quarter thermocouples (with depth shown) (○ 0.5m) (△ 0.5m) (□ 0.5m) (◇ 0.5m) (● 0.5m)
( ) Indicates thermocouples yielding partial data sets



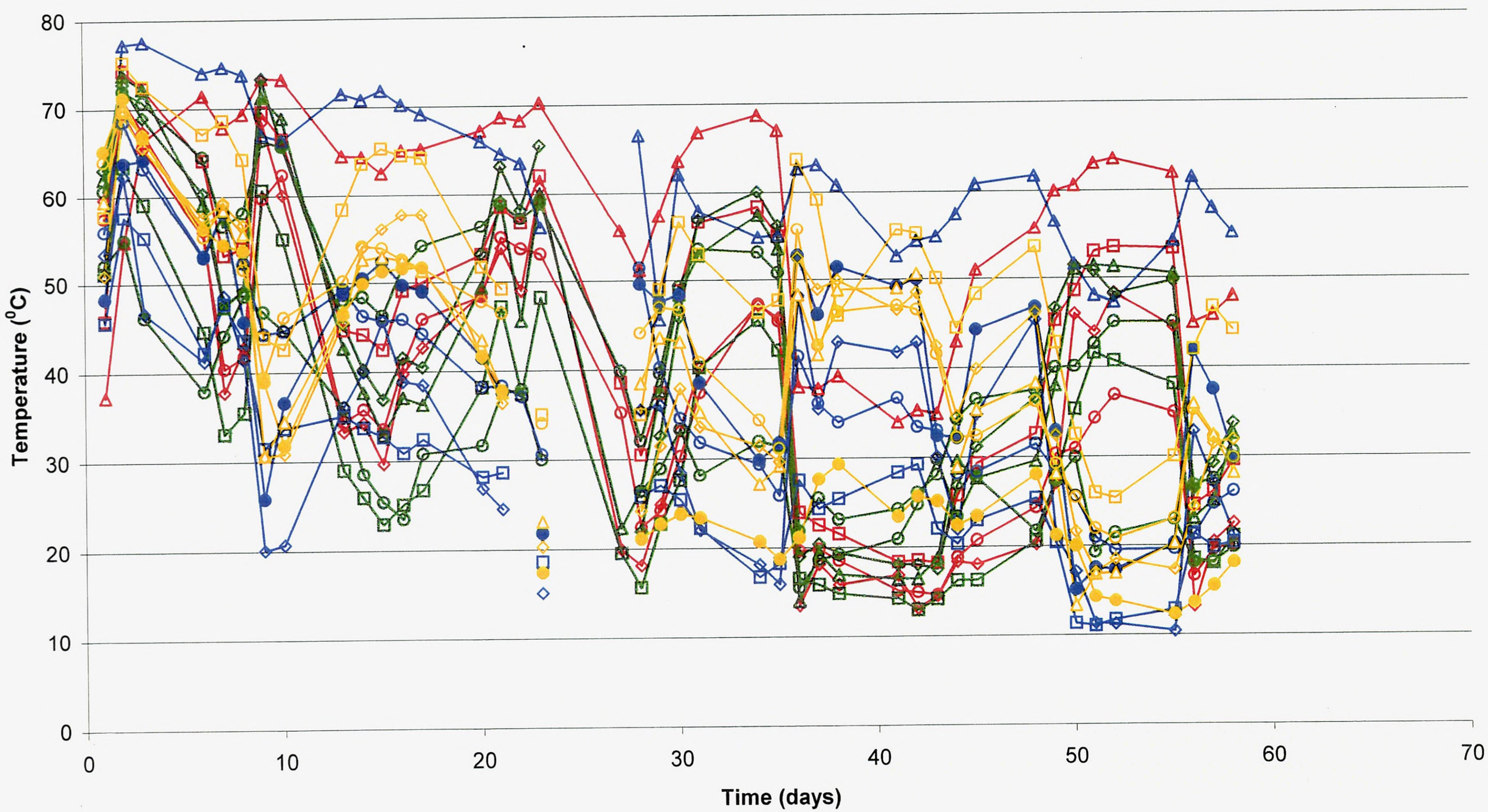
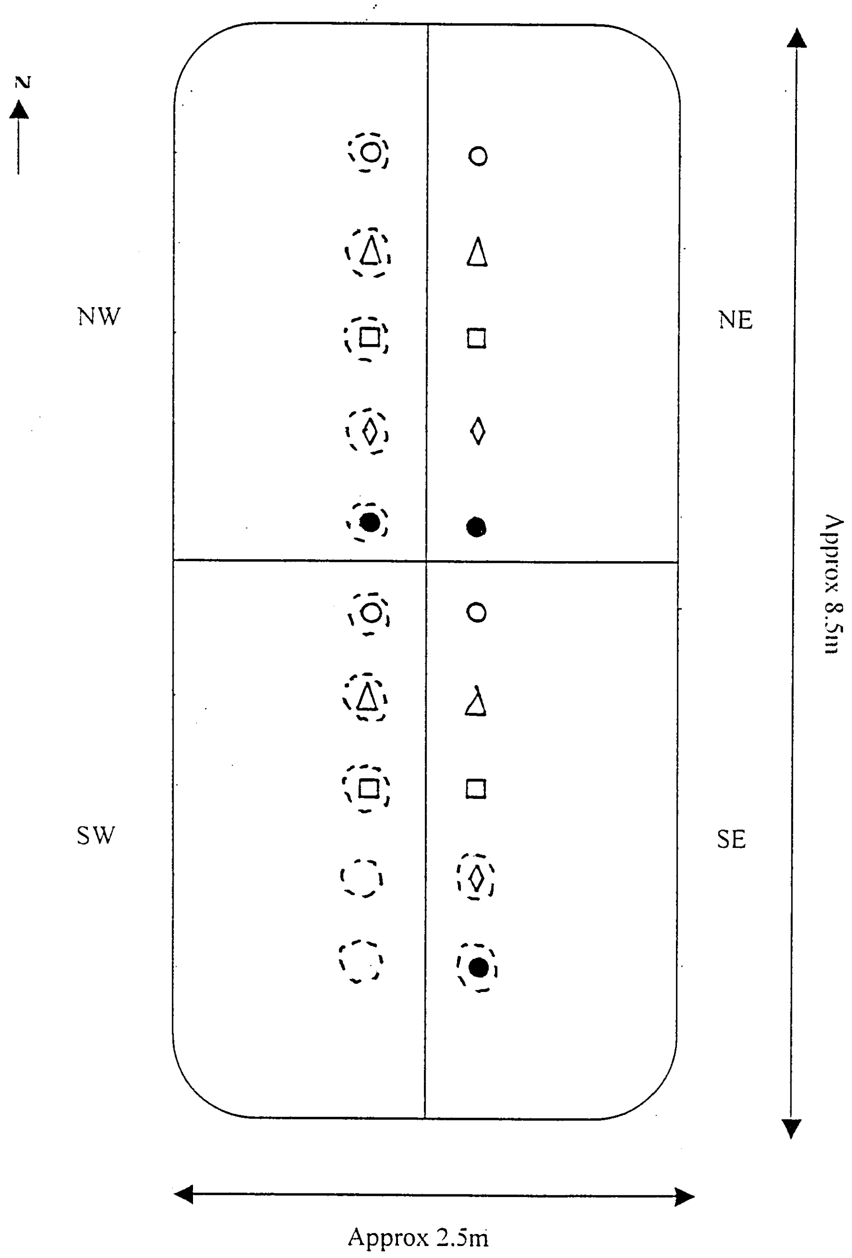
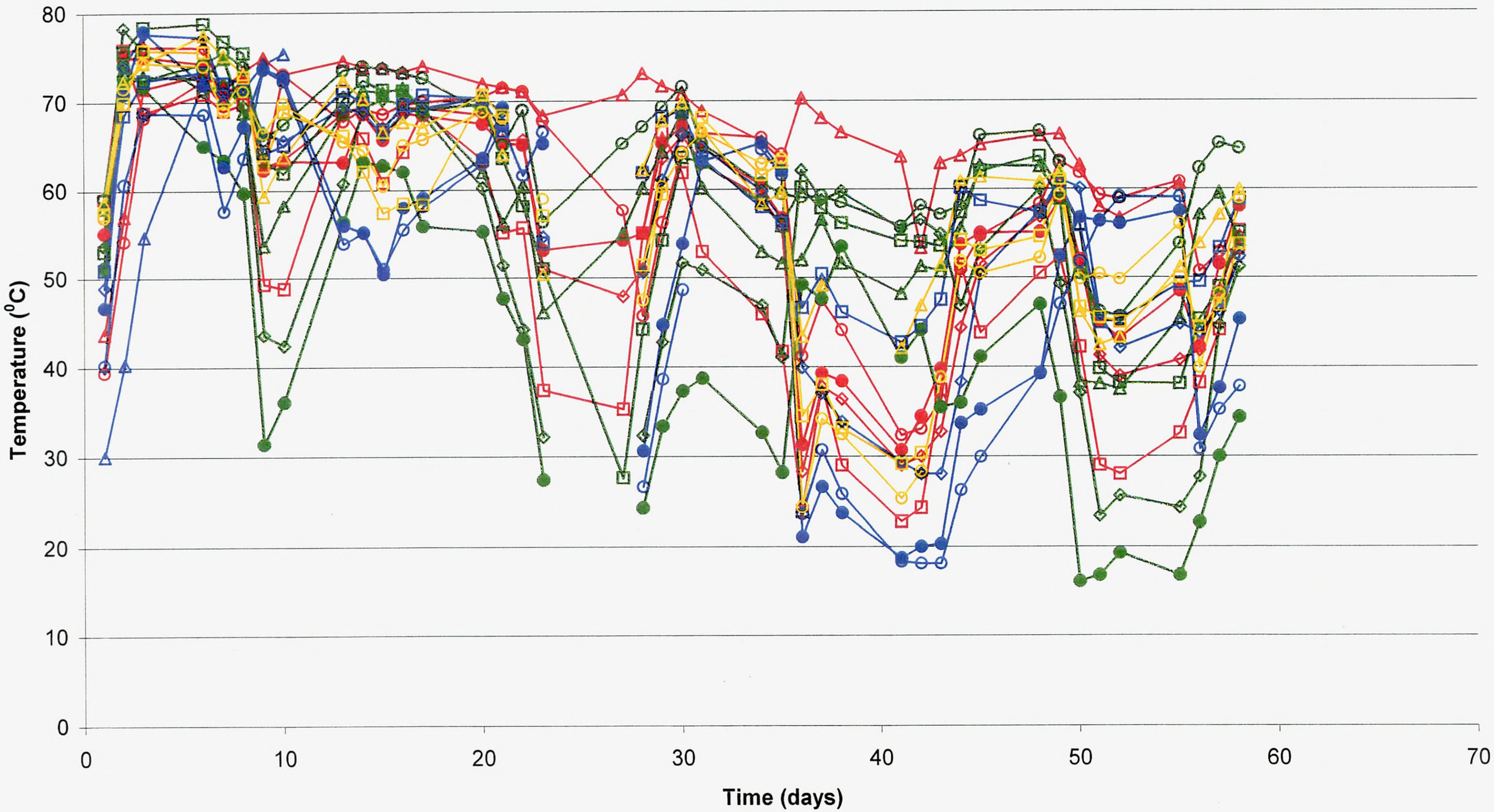

Temperature (^{0}C)
Time (days)
0
10
20
30
40
50
60
70
80

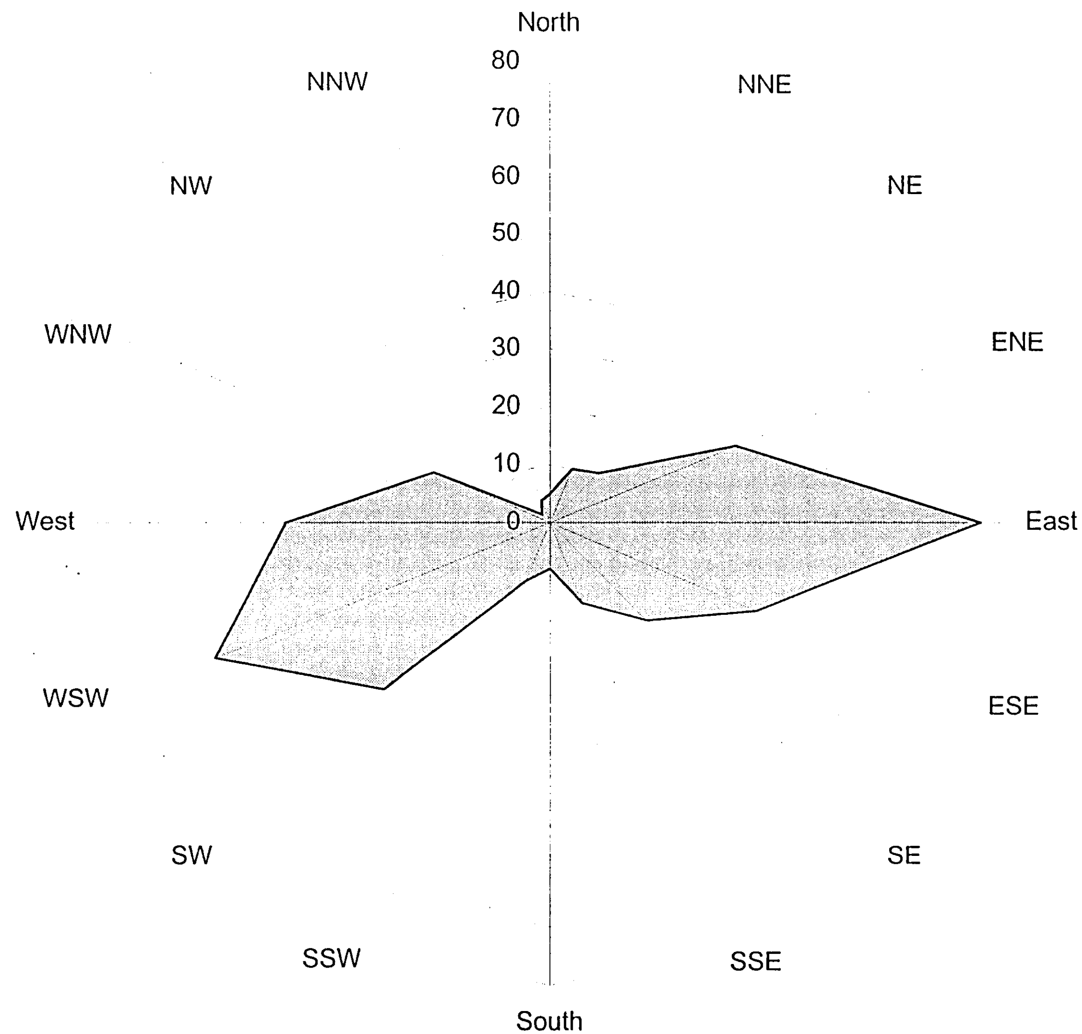
Figure 22: Riverside composting Field Trial 2 (summer) windrow temperatures (°C) Layer 3 (1m high and 1m deep) arranged by geographic quarters (NW, NE, SW, SE) over Days 1 to 58. Temperature trends from operational thermocouples as described in the diagram below are shown in relationship to their location within the windrow structure (approximate dimensions given (m)). Discontinuous data plots indicate brief periods of datalogging equipment failure. The following colours have been used to represent the windrow regions: Blue (NW), Red (NE), Yellow (SW), Green (SE).
NW quarter thermocouples (with depth shown) (**O** 1m) (△ 1m) (☐ 1m) (◇ 1m) (● 1m)
NE quarter thermocouples (with depth shown) (**O** 1m) (△ 1m) (☐ 1m) (◇ 1m) (● 1m)
SW quarter thermocouples (with depth shown) (**O** 1m) (△ 1m) (☐ 1m)
SE quarter thermocouples (with depth shown) (**O** 1m) (△ 1m) (☐ 1m) (◇ 1m) (● 1m)
( ) Indicates thermocouples yielding partial data sets





Temperature (^{0}C)
Time (days)
0
10
20
30
40
50
60
70
80

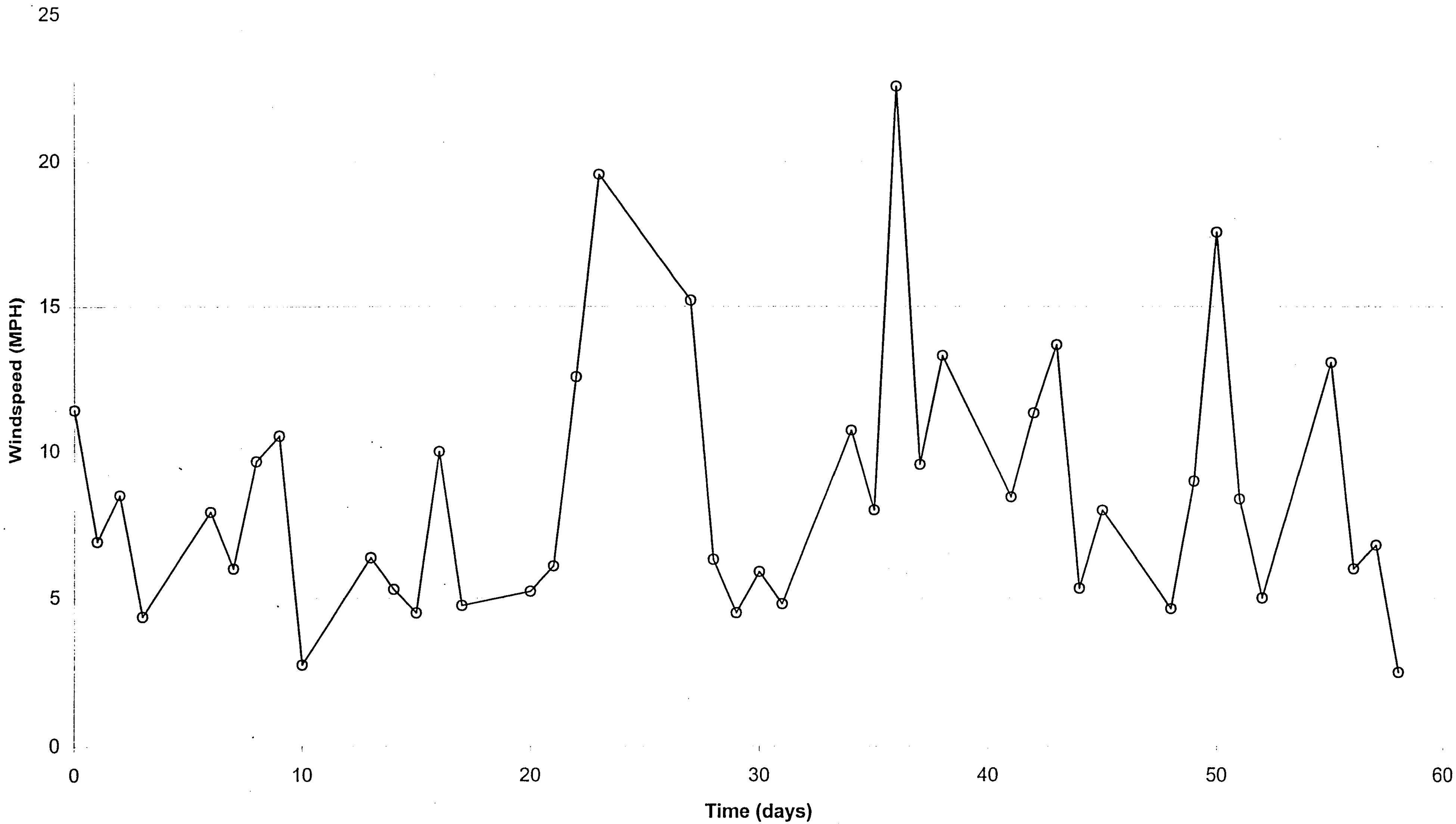
Figure 23: Riverside composting Field Trial 2 (summer). Collected wind directional data, (shaded area represents the number of readings per coordinate) showing prevailing directional trend over Days 0 to 58 of field trial. Derived from information provided by the Dundee Airport weather station (National Weather Service, Internet Weather Source, Current Weather Conditions – Dundee / Riverside, United Kingdom: http://weather.noaa.gov/weather/current/EGPN.html) adjacent to the composting site.



North
80
70
60
50
40
30
20
10
0
NNE
NE
ENE
East
ESE
SE
SSE
South
SSW
SW
WSW
West
WNW
NW
NNW

Figure 24: Riverside composting Field Trial 2 (summer). Mean windspeed in Miles Per Hour (MPH) over Days 0 to 58 of trial. Windspeed data was derived from information provided by the Dundee Airport weather station (National Weather Service, Internet Weather Source, Current Weather Conditions – Dundee / Riverside, United Kingdom: http://weather.noaa.gov/weather/current/EGPN.html) adjacent to the composting site.

(○) Mean windspeed (MPH)


25
20
15
10
5
0
Windspeed (MPH)
0
10
20
30
40
50
60
Time (days)

The low average windspeed during the first three weeks of the trial probably encouraged the prolonged development of high temperatures. It is noteworthy that the peaks in mean windspeed (days 23, 36 and 50) even although only short in duration, corresponded to points of lowered overall mean windrow temperatures, and this is also noticeable in the detailed data from individual layers, where depressions occurred around these times. Therefore, this indicates that higher mean windspeeds, above approximately 15MPH, have sufficient energy to induce a lowering in windrow temperatures, even during the summer months. When windspeeds decreased again there were increases in windrow temperature. The data from both field trials showed that increased windspeed has a direct negative effect on the development and retention of thermophilic temperatures within windrows. This action can be more pronounced if the wind blows predominately from one direction and is probably also exacerbated during the winter due to the air being colder, resulting in an increased wind chill factor. The results also show that any benefit that could be gained by increased oxygen flow to the microbial community by such increased windspeeds is diminished by the enhanced heat loss which occurs. This calls into question the benefit and effect of windrow and static pile aeration systems (particularly simple blower units) (Rynk & Richard, 2001). Generally co-designed to provide both aeration and temperature regulation for composting systems, the data from these trials suggest that without careful monitoring windrow temperatures (especially those close to blower outlets) could be negatively affected. This has implications for the production and maintenance of effective pathogen reduction temperatures within the windrow. Research by Fernandes and Sartaj (1997) that compared the effect of different forms of aeration on temperatures within static piles showed that the naturally ventilated system produced and retained the highest temperatures over other forms of aeration. This current study showed that natural environmental aeration systems, such as increased windspeed (even for short durations), can have a marked negative effect on the temperature of a windrow during both summer and winter.

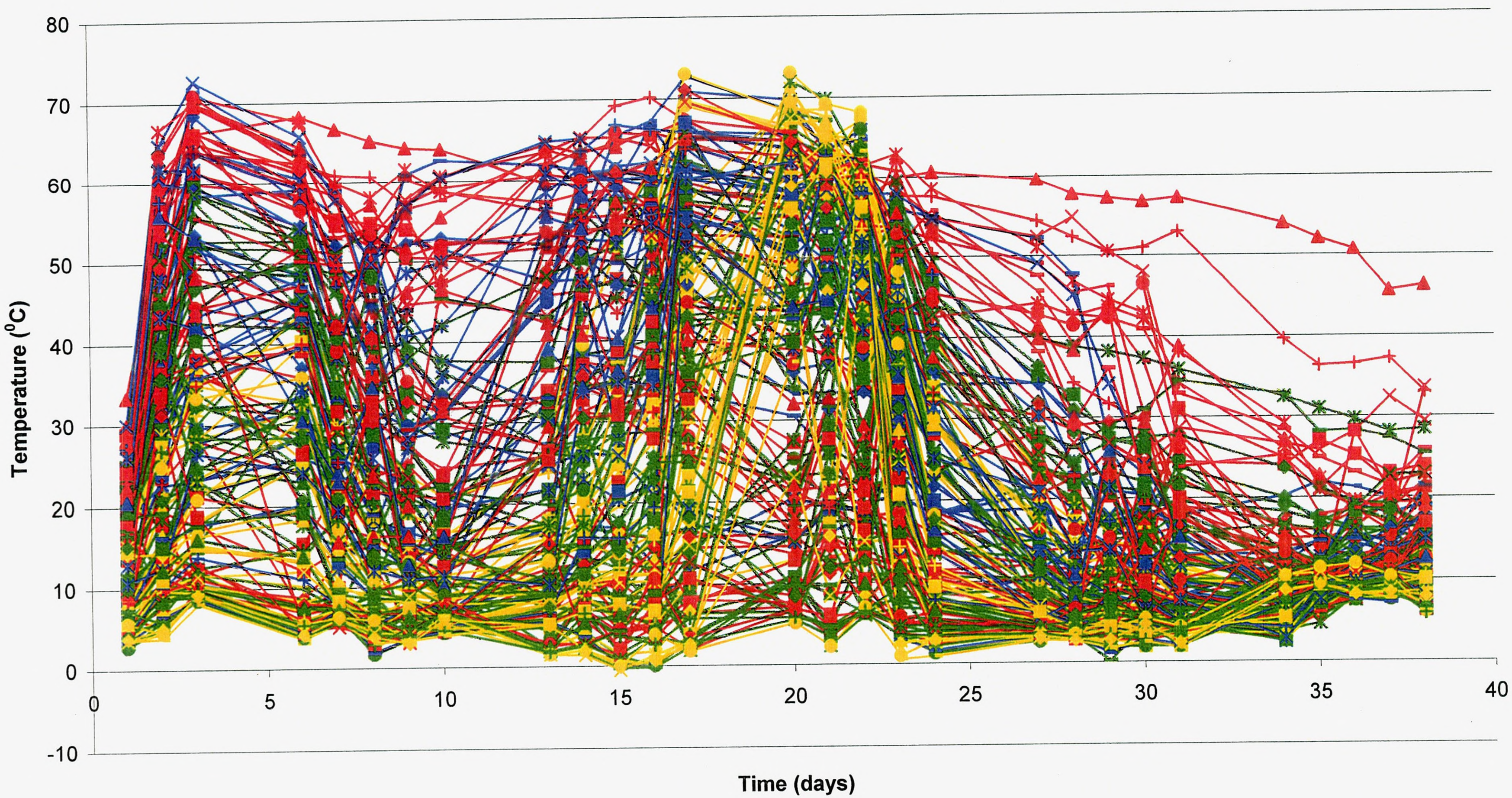
The graphs show that there was the greatest variation (range) in windrow temperature during Field Trial 2 within thermocouples positioned at depths of between 0.5m and 1m in all three layers, but especially Layers 2 and 3, of temperature measurement within the experimental windrow. These positions, regardless of height or location (NE, SE, SW, and NW), showed temperatures ranging from mesophilic to thermophilic throughout the time of the trial. The 0.5m depth temperature profile for layer 1, where although initial higher temperatures existed, these were soon replaced by mesophilic temperatures for the main period of the trial. This suggests the area near the base and close to the windrow's widest point was too remote from the hotter core regions and externally exposed to retain elevated temperatures (insulation limited). Thermophilic temperatures were most prolonged within Layer 1 at a depth of 1.5m and Layer 2 at a depth of 1m, these parts of the windrow presumably experienced a combination of favourable physical-chemical conditions and sufficient insulational capacity to allow continued thermophilic activity. Such results demonstrate clearly that the prolonged maintenance of highly thermophilic (above 60°C) temperatures are not detrimental to the microbial community, since if they were, the community would display a decline in activity and a resultant drop in temperature (even with good insulation without a source of heat, there would be a slow, but defined downward trend), this was not the case. However, within other parts (the less "blanketed" zones) of the windrow structure there was clear evidence that external environmental factors affected the temperatures internally, with depressions linked to increased windspeed for example (Days 23, 36 & 50). It is also possible that microbial succession events and their related temperature trends (dips and peaks) were more clearly seen here, as they were not masked by over-insulation as would occur in the core regions (Layer 1 1.5m deep and Layer 2 1m deep). Layer 3 temperatures, regardless of depth, showed a broad varied trend with many fluctuations present. This suggests that, in a similar fashion to the upper layers of Field Trial 1 the reduced cross-sectional depth and resultant loss of insulation and more open structure (due to less compressive forces) led to a loss in the thermal retention of this region of a windrow.

It can be reasoned therefore, that thermophilic temperature development within a windrow is related to depth and height within the structure. Feedstocks within the lowest and broadest regions of the structure at 0.5m depth did not display prolonged thermophilic temperatures, although elevated temperatures were exhibited during the first few days. At a depth of 1m there was substantial development of thermophilic temperatures, but there were still some mesophilic temperatures exhibited. At a depth of 1.5m within lower levels of the windrow, thermophilic temperatures were quickly reached and remained in this condition for extended periods. Middle region thermocouples at a depth of 0.5m showed a wide range of temperatures spanning mesophilic and thermophilic conditions. This was suggestive that the windrow at this height and depth were very much at the interface between mesophilic and thermophilic temperature regimes. Core temperatures (1m depth) at this height quickly developed and retained high temperatures. Upper levels of the windrow exhibited similar temperatures at both 0.5m and 1m depths, with a wide-ranging temperature profile. These findings showed that, even in a windrow displaying an overall temperature trend exhibiting prolonged thermophilic conditions (which would meet many of the established criteria for potential pathogen reduction within a windrow) large volumes of the waste materials did not heat up and maintain thermophilic temperatures, even within subsurface areas of 1m depth. The results suggest that a large percentage of the windrow actually failed to reach and / or maintain sufficiently high temperatures to reduce pathogens to normal background levels. It can be suggested that windrows using green wastes should be of sufficient dimensions to ensure that there is enough insulating mass within the structure to limit the heat loss to the external environment, due to both insufficient bulk, larger surface area and the effects of wind chill on the structure, thus enabling maximal development of thermophilic conditions with the windrow. The content of such windrows should be turned to ensure the efficient mixing of their contents, allowing the greatest amount of material to be positioned within the inner-core region of the structure, to give good assurance of potential pathogen reduction. The data showed that poor gas exchange (i.e. lack of oxygen for metabolism) was not a limiting factor on the maintenance of thermophilic conditions within the deepest regions of the windrow, even at the lower levels where greater compression was likely. Therefore this would indicate that the primary need to turn such windrows was to ensure the mixing of the contents and not aeration.

COMPLEXITY OF WINDROW TEMPERATURE TRENDS REVEALED

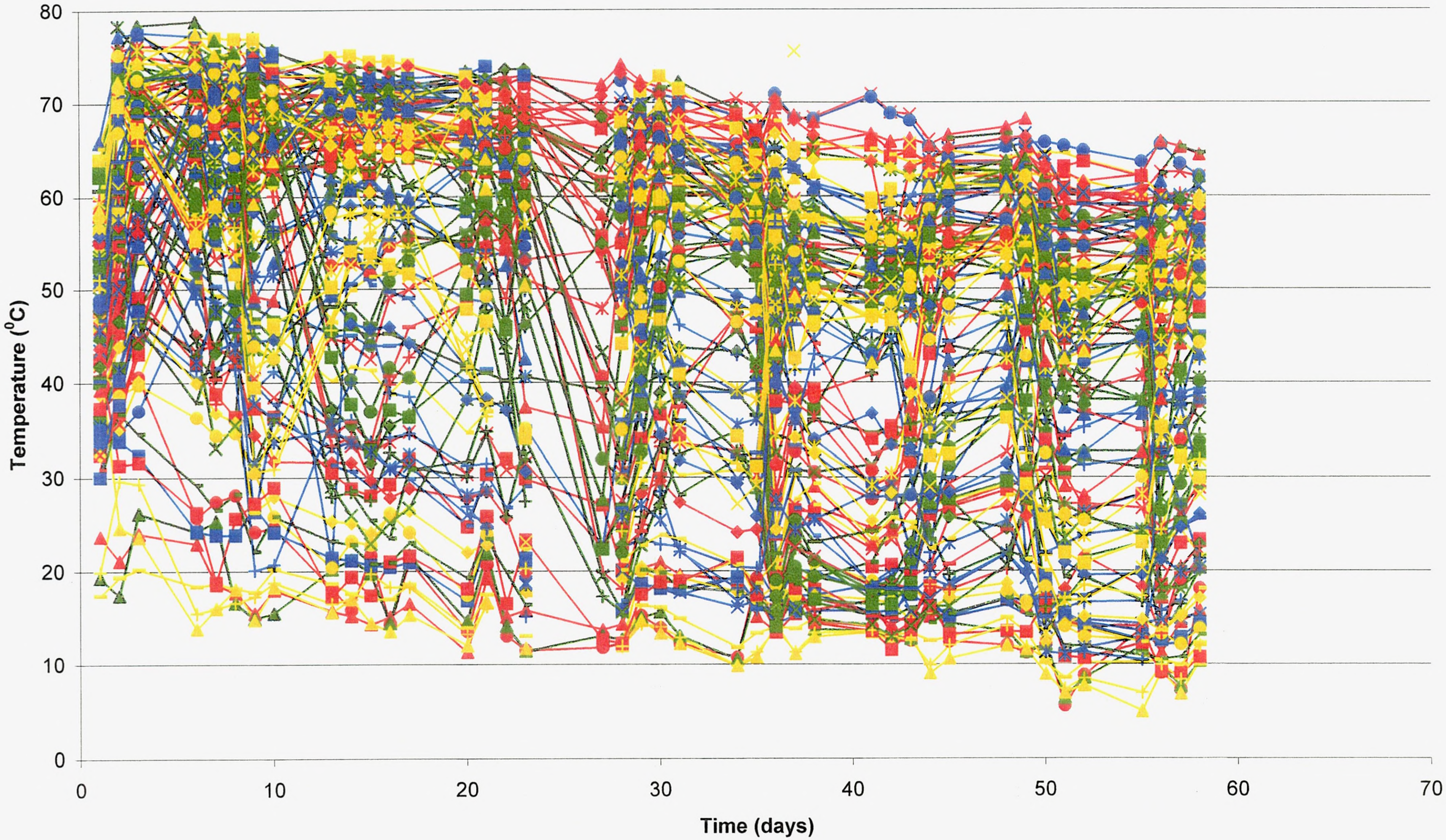
Figures 25 and 26 reveal the overall complexity of temperature movements within both of the experimental windrows, by showing each of the readings of all the operational thermocouples (arranged by geographic quarters (NE, NW, SE, and SW) against time. The graphs uniquely show the major flows of temperature within the structure over time (related to microbial succession, external or internal forces) and clearly demonstrate that, although substantial enough to create identifiable dips and peaks, these in no way involve all parts of the windrow, (i.e. large parts of the windrows, in terms of temperature were unaffected by these so-called major temperature changes). This suggests that the windrows did not act as single entities (in terms of microbial activity and heat generation), but as series of separate but interrelated units, which heated up and cooled down according to local circumstances (during the active phase of composting). This reflected the heterogeneity of the feedstocks and the typical "mixed" structure of a windrow. Although both trials were carried out at different times of the year and with green waste feedstocks, which reflected this seasonality, the range of temperatures exhibited in both trials was very similar (approximately 60°C to 70°C above the ambient temperature during the most active phase of each of the composting processes). This implies that, in general terms, the activity during both trials was essentially similar, although the length of widespread thermophilic conditions was shorter in Field Trial 1 than Field Trial 2.

Figure 25: Riverside composting Field Trial 1 (winter) windrow temperature plots (°C) over Days 1 to 38. Temperature trends from all operational thermocouples on an individual basis are presented. The graph is employed to indicate the gross temperature patterns and fluctuations therein within the windrow over Days 1 to 38 of the field trial. The temperature plots have been arranged by geographic quarters (NW, NE, SW, and SE). The following colours have been used to represent the windrow regions: Blue (NW), Red (NE), Yellow (SW) and Green (SE).



80
70
60
50
40
30
20
10
0
-10
Temperature (^{0}C)
0
5
10
15
20
25
30
35
40
Time (days)

Figure 26: Riverside composting Field Trial 2 (summer) windrow temperature plots (°C) over Days 1 to 58. Temperature trends from all operational thermocouples on an individual basis are presented. The graph is employed to indicate the gross temperature patterns and fluctuations therein within the windrow over Days 1 to 58 of the field trial. The temperature plots have been arranged by geographic quarters (NW, NE, SW, and SE). The following colours have been used to represent the windrow regions: Blue (NW), Red (NE), Yellow (SW) and Green (SE). Discontinuous data plots indicate brief periods of data logging equipment failure.



80
70
60
50
40
30
20
10
0
Temperature (^{0}C)
0
10
20
30
40
50
60
70
Time (days)

This was probably due to differences in the decompositional ease, nature of the feedstocks and patterns of wind behaviour at different times of year, suggesting that winter-built windrows require a greater level of feedstock management and windrow maintenance to ensure efficient composting. This difference is most marked when the end points of each graph are observed (day 38 for Field Trial 1 and day 58 for Field Trial 2). Field Trial 1 showed a narrow banded mesophilic pattern with temperature values mirroring those at establishment. Whilst Field Trial 2 displayed a broad band of temperature values, many still thermophilic and the overall temperature pattern showed little change over the monitored period (i.e. a wide range of temperatures between two relatively fixed points). It also demonstrates that ambient temperature had no noticeable effect on the heating characteristics of the windrows, and that other factors both internal and external were responsible for the production of temperature trends within the structure. Statistical analysis of data for any correlation between mean windrow temperature and ambient temperature, showed that for Field Trial 1 there was a negative correlation coefficient of –0.328 over days 1 to 38 (i.e. low ambient temperatures resulted in high windrow temperatures) and for data from Field Trial 2 a positive correlation coefficient of +0.260 (i.e. high ambient temperatures resulted in high windrow temperatures) for a similar time period. This difference can be explained by the fact the Trial 1 was established during the winter and ran until spring, with, lowest ambient temperatures at the earlier most active stages, and conversely the second trial ran from summer to autumn, when highest ambient temperatures and windrow temperatures were united. Windrow temperature trends are driven by the microbial processes possible within the structure at a given time, and this has been shown to be the case regardless of seasonal temperature trends.

DISTRIBUTION AND FREQUENCY OF TEMPERATURES WITHIN WINDROWS

Data analysis of the temperature readings from the experimental windrows revealed both the spread and frequency of temperature levels within the windrows down to the level of the different layers employed for the placement of thermocouples. Figure 27 shows the frequency and distribution of temperature readings (in 5°C intervals) by percentage over day 1 to 38 for each of the five temperature monitoring layers (ranging from 0.2m to 2m high, and the following depths; Layers 1 and 2, 0.5m, 1m and 2m; Layers 3 and 4, 0.5m and 1m; and Layer 5, 0.5m) for Field Trial 1. There is a clear skew to the left, (i.e. the lower temperature bands; psychrotrophic and mesophilic). This was true for all windrow layers especially the upper ones, as over 35% of readings for layer 5 occurred within the temperature interval of 10°C to 15°C. Interestingly, layer 1 had the greatest percentage of readings between 25°C and 40°C compared to the other layers. This may suggest that a more diverse range of microbial niches was present in layer 1 compared to the other layers. The data show that over the monitored period of days 1 to 38, readings falling within the 55°C to 60°C band (typically quoted as an ideal potential pathogen reduction temperature) only accounted for 5% of the total number of temperature readings for layers 1 to 4 and much less for layer 5 of the windrow. Calculation has shown that the mean figure for all windrow layers reaching and / or exceeding 55°C for the trial period was 12.8% of total temperature readings. Layer 3 recorded a value of 18.3% during this period. The data demonstrate that for layers 1 to 4 there was an essentially even distribution of temperature readings within each of the 5°C temperature intervals, which indicates that overall temperature patterns (maxima, minima and trends) were broadly similar. The data also show that temperature conditions existed within the windrow for the potential growth of a wide range of microorganisms of psychrotrophic and mesophilic types (potential pathogens) as well as thermophiles during the period of the trial.

Figure 27: Riverside composting Field Trial 1 (winter). Percentage of temperature readings (°C) in different temperature ranges (-5°C to 85°C+ in five degree intervals) over Days 1 to 38 of the field trial at five windrow heights termed layers where thermocouples were positioned at varying depths.

Layer 1 indicates temperature readings from a height of 0.2m and depths of 0.5m, 1m and 2m. Layer 2 indicates temperature readings from a height of 0.5m and depths of 0.5m, 1m and 2m. Layer 3 indicates temperature readings from a height of 1m and depths of 0.5m and 1m. Layer 4 indicates temperature readings from a height of 1.5m and depths of 0.5m and 1m. Layer 5 indicates temperature readings from a height of 2m and a depth of 0.5m.

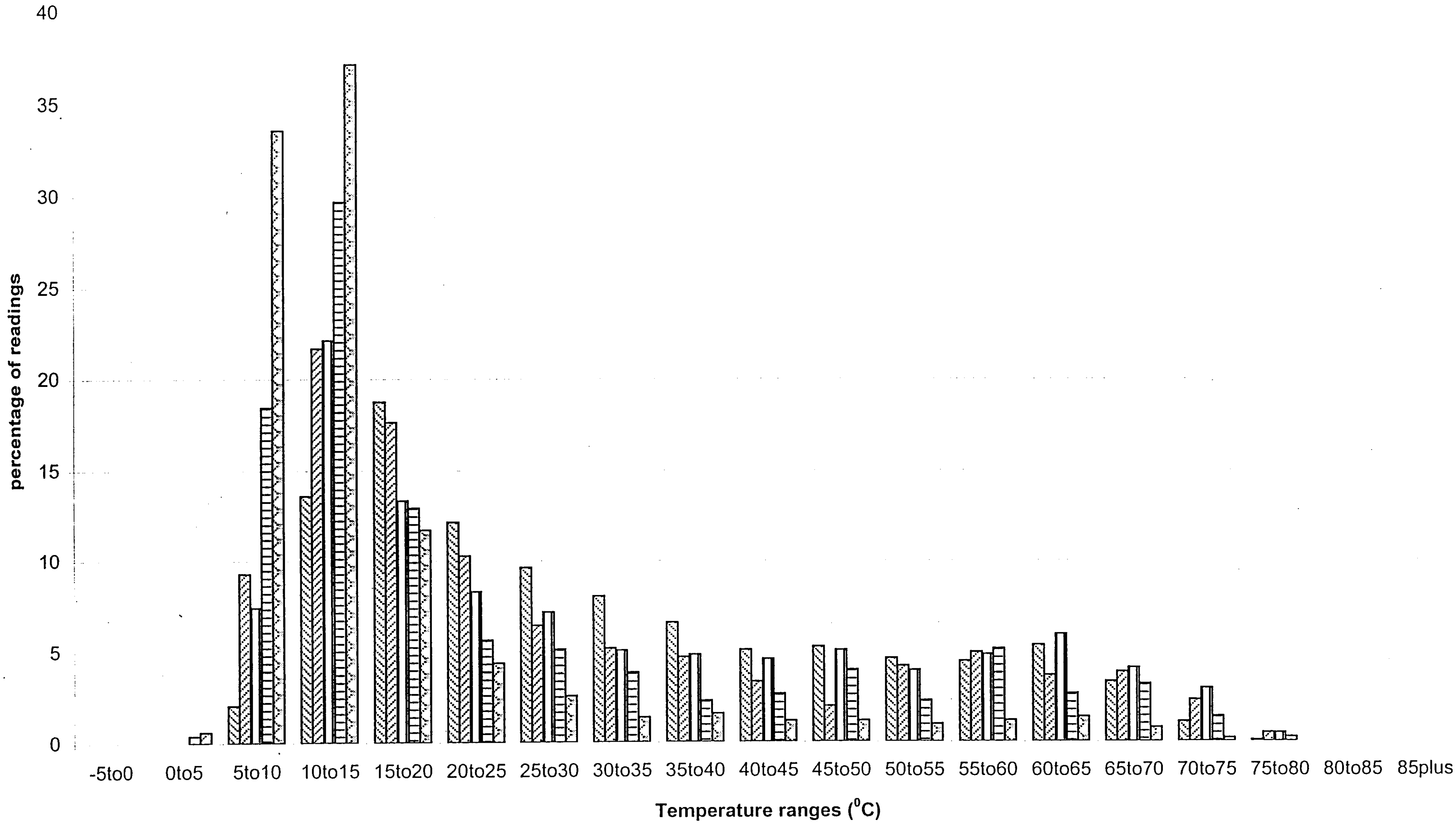
( ) Layer 1

( ) Layer 2

( ) Layer 3

( ) Layer 4

( ) Layer 5


40
35
30
25
20
15
10
5
0
percentage of readings
-5to0
0to5
5to10
10to15
15to20
20to25
25to30
30to35
35to40
40to45
45to50
50to55
55to60
60to65
65to70
70to75
75to80
80to85
85plus
Temperature ranges (^{0}C)

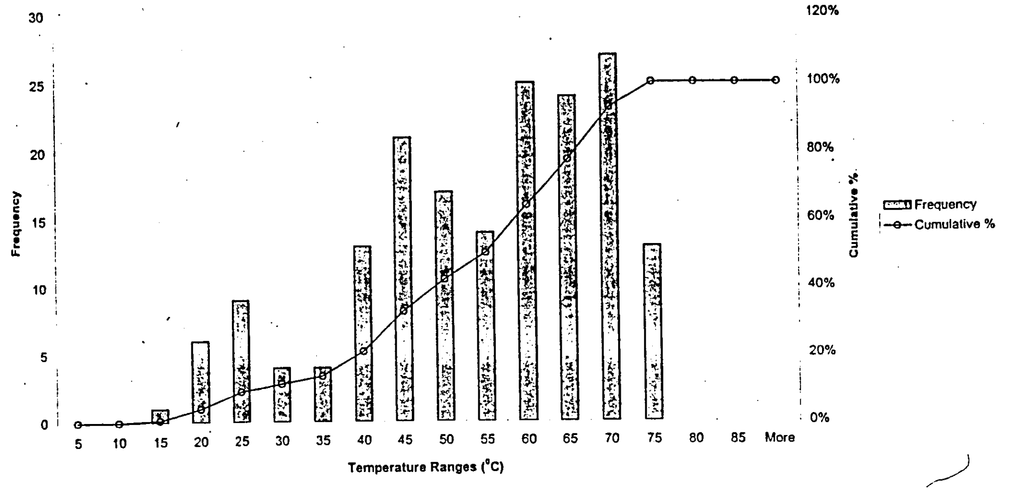
THE PATTERN OF FREQUENCY AND DISTRIBUTION OF TEMPERATURES ON A WEEKLY BASIS WITHIN A SUMMER ESTABLISHED WINDROW.

The following set of figures (28a-f, 29a-f & 30a-f) reveal the nature of temperature distribution (by preset intervals of 5°C) and its frequency in terms of number of readings on a weekly basis for each of the three windrow layers used for temperature determination during the, summer established experimental windrow (Field Trial 2).

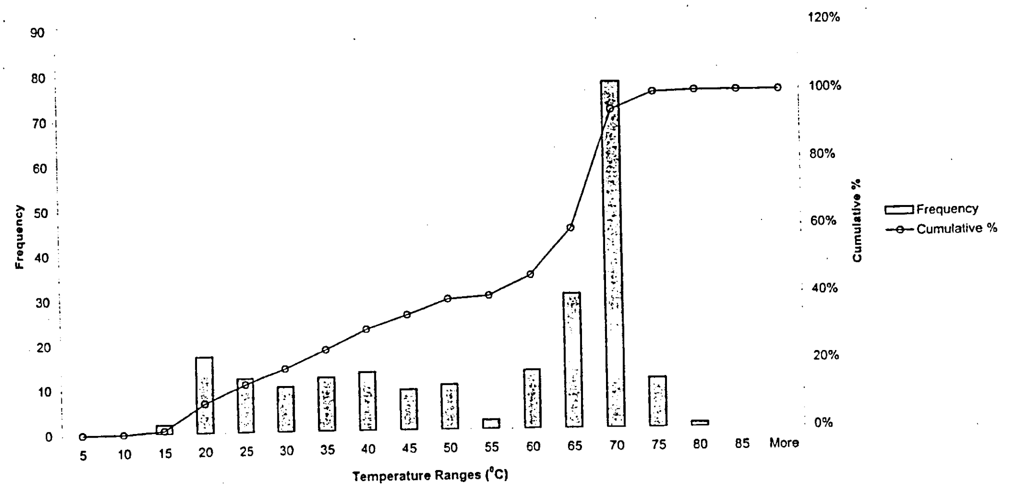
There were differences between each layer of the windrow, in the spread and frequency of temperature readings over the first seven days of the trial. Layer 1, within the region of greatest cross-sectional mass, showed the largest spread of temperature readings, with clear activity over the range from the 10°C to 15°C band to 75°C to 80°C interval. There were significant numbers of readings within the mesophilic and thermophilic temperature zones, and the daily temperature readings for this period showed an interesting division between those regions of layer 1 (mainly the deeper parts), which displayed a sustained increase in temperature, and the other parts (the outermost regions) and had a downward trend. This can be compared with layers 2 and 3, where a skew to the right is observable. Here there were few readings recorded in the lower temperature intervals, which suggest a much stronger thermophilic presence within these layers, indicating ideal composting conditions occurred in these areas of the windrow assessed at this time. During the Day 8 to 14 time period, there was a marked predominance of thermophilic temperature readings within all layers (75°C to 80°C interval), although layer 1 continued to show some diversity, and layer 3 showed a wider cross-section of temperature readings, many within the mesophilic ranges. This pattern was continued during Days 15 to 21. Days 22 to 28 started to show a wider range of temperature readings within layers 1 and 2 and a marked increase in the numbers of mesophilic range temperature readings in layer 3. This reflects a time when there was a general downward trend in temperatures within the windrow and is believed to be linked to an increase in the windspeed during this time resulting in elevated heat loss from the windrow.

Figure 28: Riverside composting Field Trial 2 (summer). Temperature distribution histograms. a) Windrow Layer 1, Days 1 to 7; b) Windrow Layer 1, Days 8 to 14; c) Windrow Layer 1, Days 15 to 21; d) Windrow Layer 1, Days 22 to 28; e) Windrow Layer 1, Days 29 to 35; f) Windrow Layer 1, Days 36 to 42.

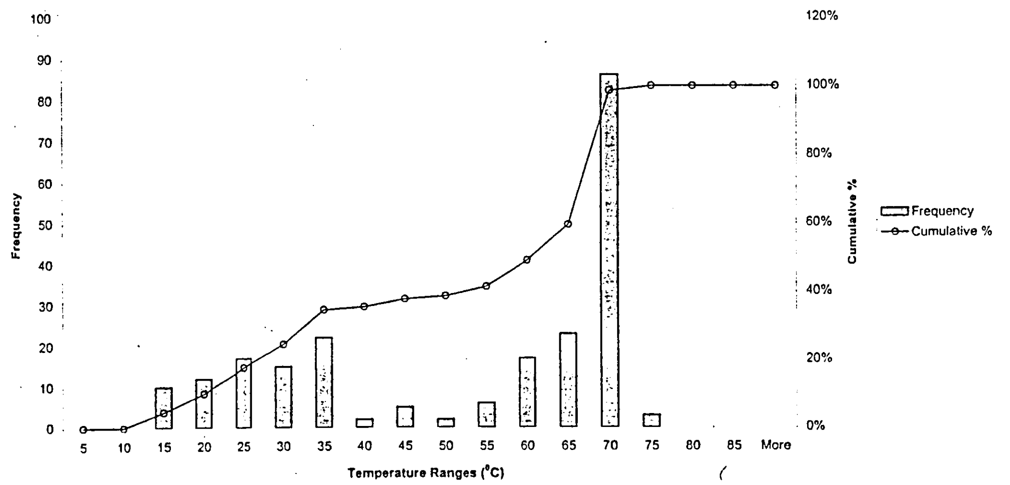
a)


Frequency
Cumulative %
Temperature Ranges (°C)
5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 More
0 5 10 15 20 25 30
0% 20% 40% 60% 80% 100% 120%

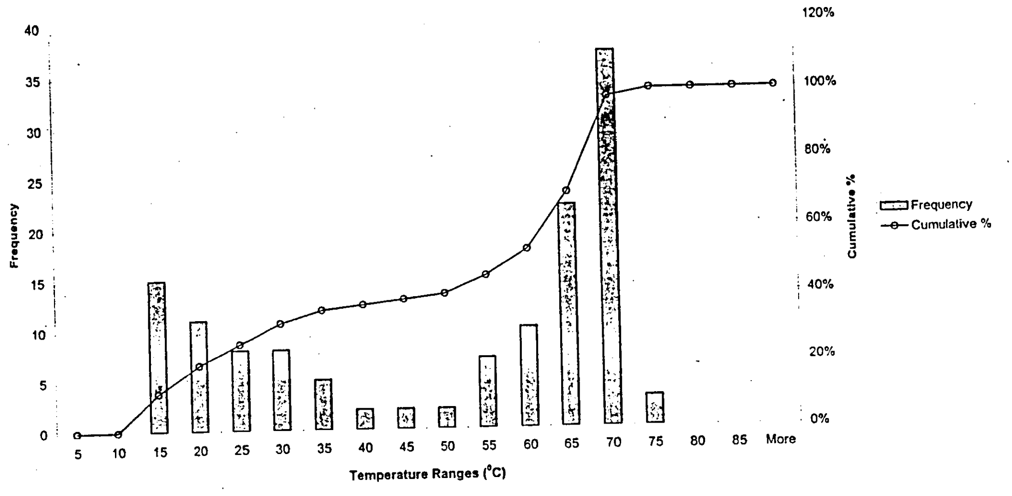
b)


Frequency
Cumulative %
Temperature Ranges (°C)
5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 More
0 10 20 30 40 50 60 70 80 90
0% 20% 40% 60% 80% 100% 120%

c)

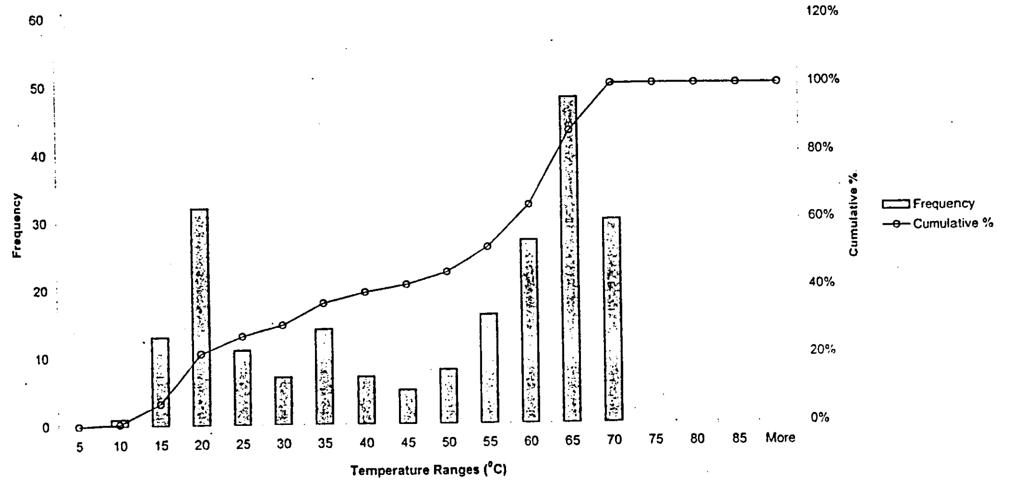

Frequency
Cumulative %
Temperature Ranges (°C)
5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 More
0 10 20 30 40 50 60 70 80 90 100
0% 20% 40% 60% 80% 100% 120%

d)



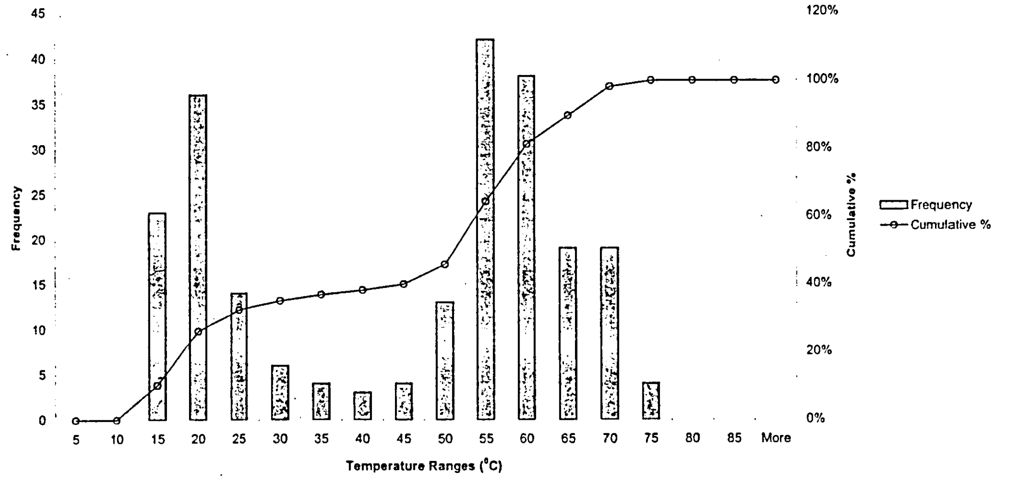
Frequency
Cumulative %
Temperature Ranges (°C)
5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 More

e)



Frequency
Cumulative %
Temperature Ranges (°C)
5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 More

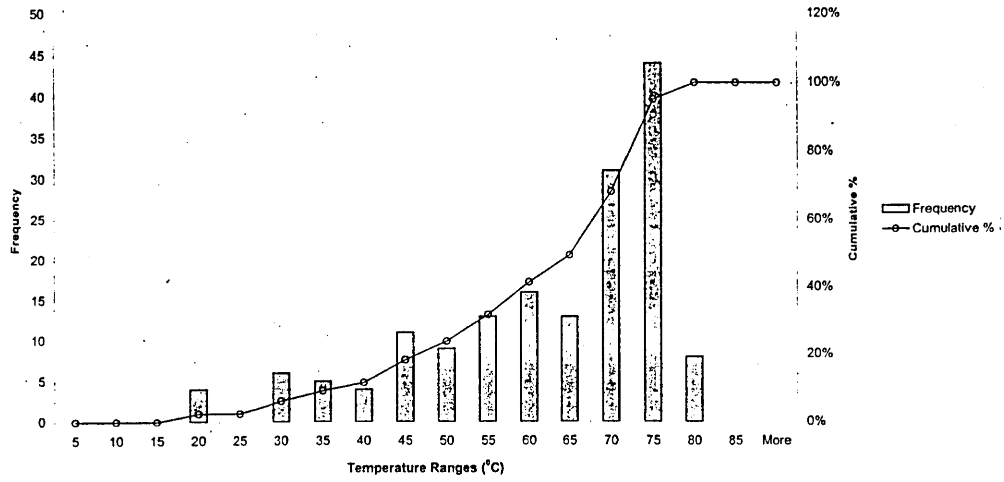
f)



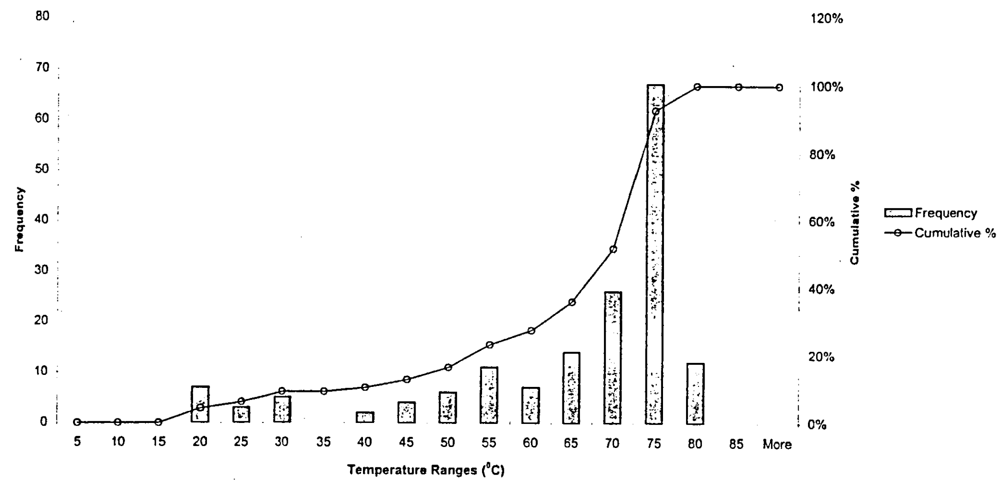
Frequency
Cumulative %
Temperature Ranges (°C)
5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 More

Figure 29: Riverside composting Field Trial 2 (summer). Temperature distribution histograms. a) Windrow Layer 2, Days 1 to 7; b) Windrow Layer 2, Days 8 to 14; c) Windrow Layer 2, Days 15 to 21; d) Windrow Layer 2, Days 22 to 28; e) Windrow Layer 2, Days 29 to 35; f) Windrow Layer 2, Days 36 to 42.

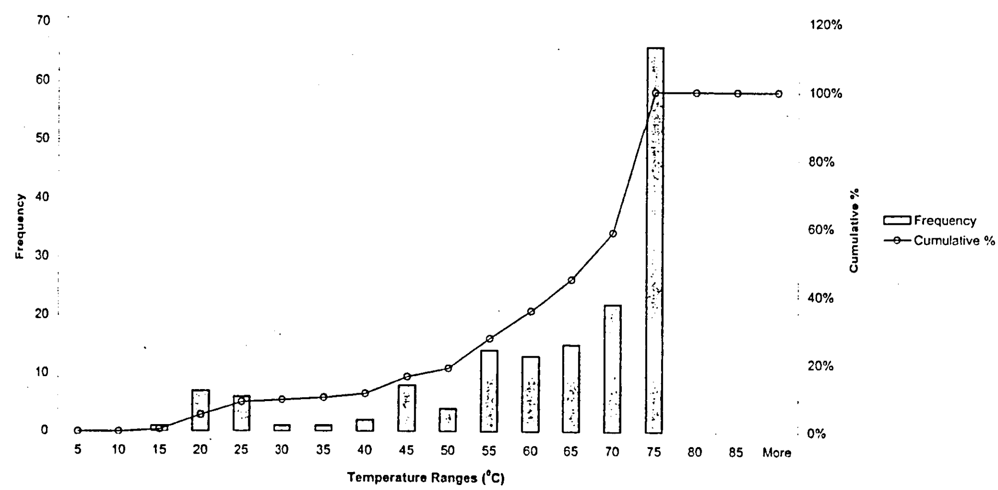
a)


Frequency
Cumulative %
Temperature Ranges (°C)
Frequency
Cumulative %

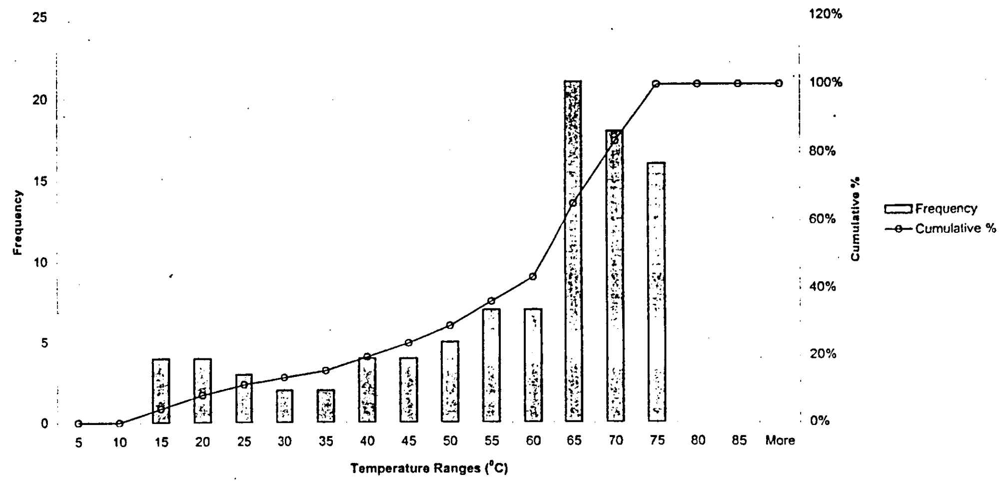
b)


Frequency
Cumulative %
Temperature Ranges (°C)
Frequency
Cumulative %

c)

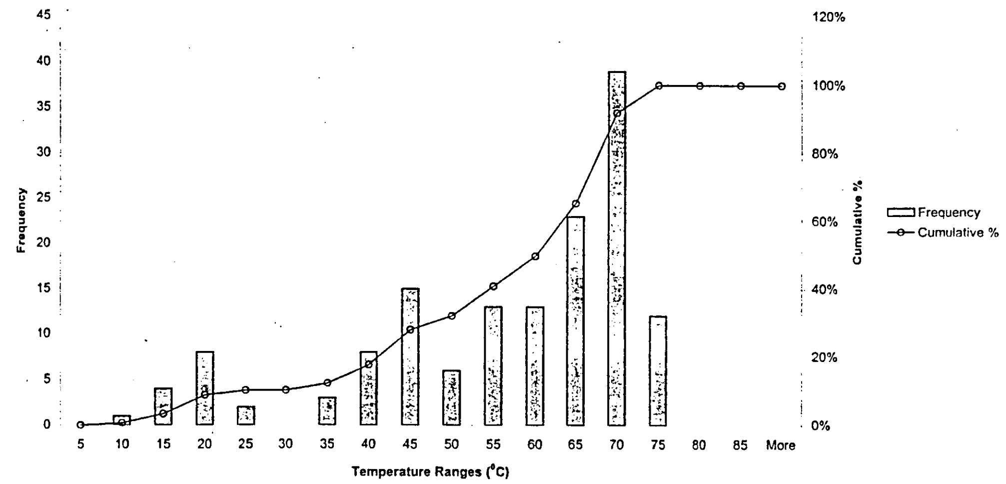

Frequency
Cumulative %
Temperature Ranges (°C)
Frequency
Cumulative %

d)



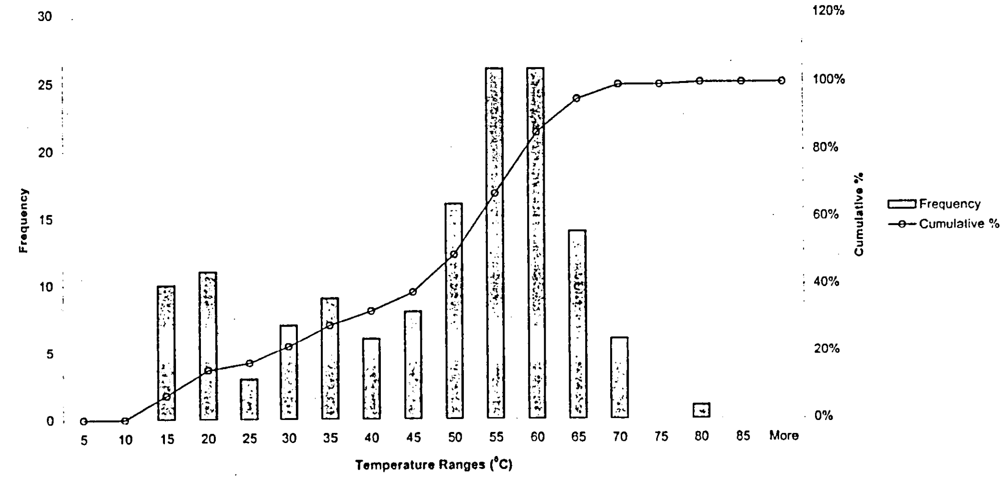
Frequency
Cumulative %
Temperature Ranges (°C)
5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 More
0 5 10 15 20 25
0% 20% 40% 60% 80% 100% 120%
Frequency
Cumulative %

e)



Frequency
Cumulative %
Temperature Ranges (°C)
5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 More
0 5 10 15 20 25 30 35 40 45
0% 20% 40% 60% 80% 100% 120%
Frequency
Cumulative %

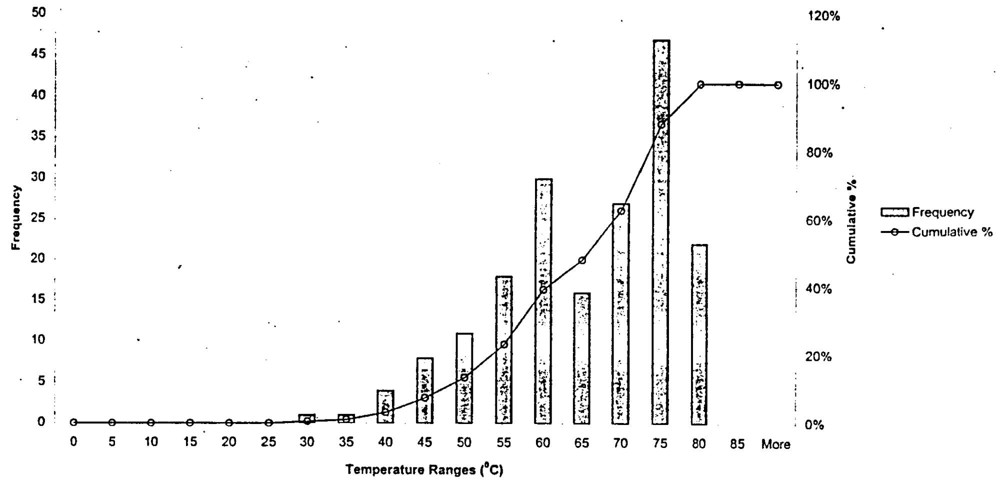
f)



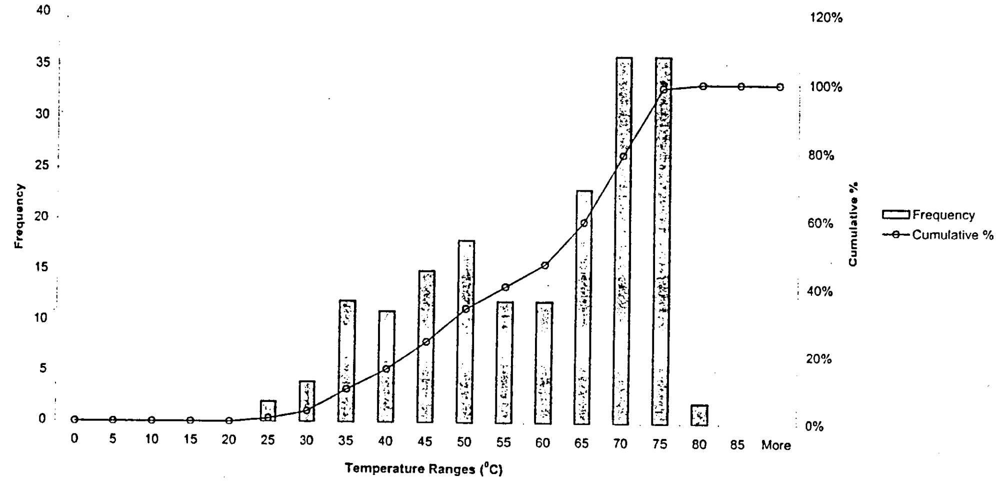
Frequency
Cumulative %
Temperature Ranges (°C)
5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 More
0 5 10 15 20 25 30
0% 20% 40% 60% 80% 100% 120%
Frequency
Cumulative %

Figure 30: Riverside composting Field Trial 2 (summer). Temperature distribution histograms. a) Windrow Layer 3, Days 1 to 7; b) Windrow Layer 3, Days 8 to 14; c) Windrow Layer 3, Days 15 to 21; d) Windrow Layer 3, Days 22 to 28; e) Windrow Layer 3, Days 29 to 35; f) Windrow Layer 3, Days 36 to 42.

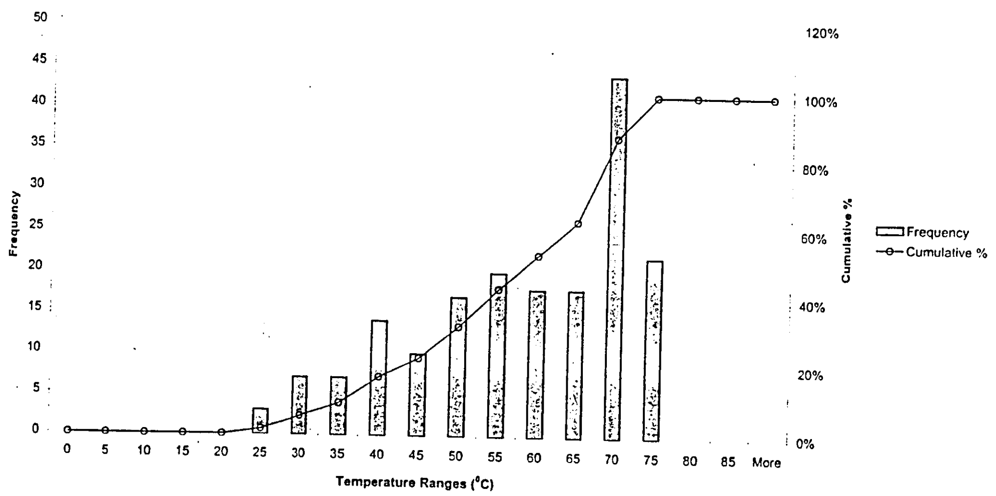
a)


Frequency
Cumulative %
Temperature Ranges (°C)
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 More
Frequency
Cumulative %

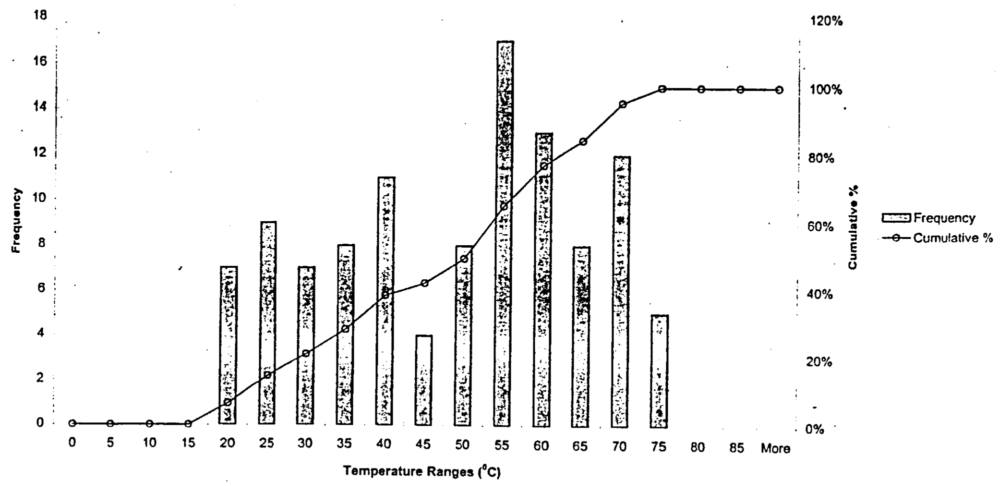
b)


Frequency
Cumulative %
Temperature Ranges (°C)
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 More
Frequency
Cumulative %

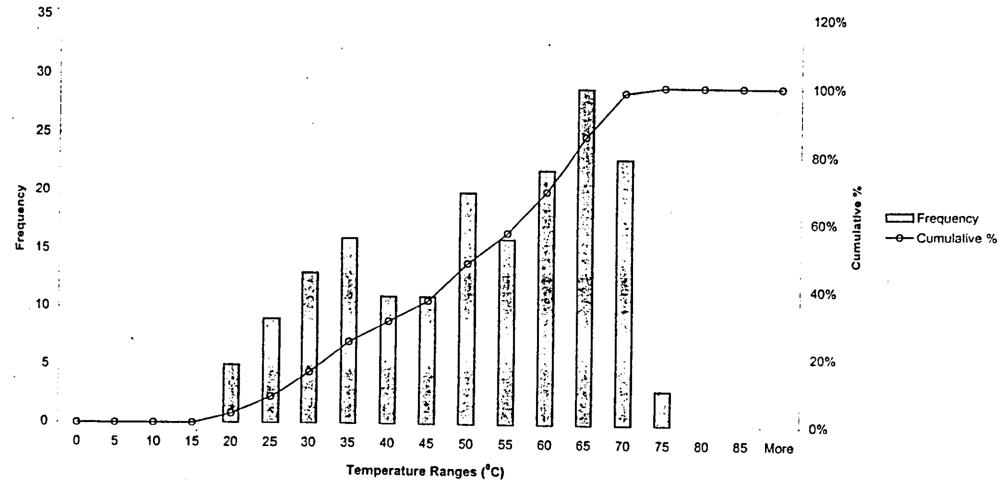
c)


Frequency
Cumulative %
Temperature Ranges (°C)
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 More
Frequency
Cumulative %

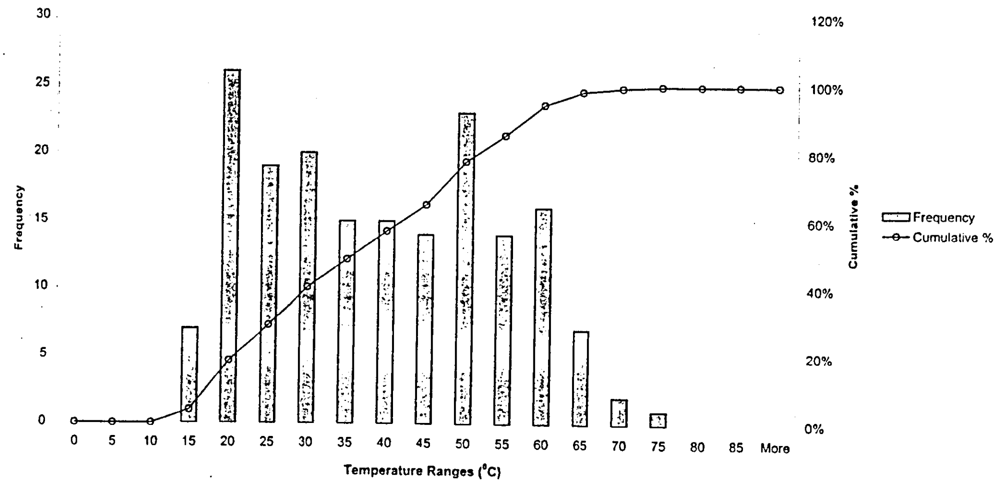
d)


Frequency
Cumulative %
Temperature Ranges (°C)
Frequency
Cumulative %

e)


Frequency
Cumulative %
Temperature Ranges (°C)
Frequency
Cumulative %

f)


Frequency
Cumulative %
Temperature Ranges (°C)
Frequency
Cumulative %

Between Days 29 to 35, an essentially static pattern for layer 1, a return to more thermophilic temperatures for layer 2 and slight recovery for layer 3 was demonstrated, but there was still a broad range of temperature readings present. Within the time period of day 36 to 42 there was again a noticeable shift towards the cooler temperature bands occurring in all three layers of the windrow. This can be compared to the downward trend shown by the daily temperature plots for this time period.

The data displayed within the above figures using frequency histograms show that this technique can provide a valuable tool to aid in the assessment of temperature trends within a windrow over a period of time, which can be directly linked to plots of daily temperature readings. The temperature trends displayed by an active composting system are very important in both the assessment of the efficiency of microbial decomposition of organic material (and turning requirements etc), and the assurance of effective pathogen reduction, which is dependant on exposing the greatest volume of material to sufficiently high temperatures for long enough (exposure time) to kill the majority of potential pathogens. The displaying of temperature data in the above manner allows the composter to easily visualize both the spread of temperature values (the upper and lower limits and the distribution (even or skewed, i.e. mainly mesophilic or thermophilic in nature) can be assessed) and the number (frequency) of the temperature readings taken during a time period falling within each of the temperature intervals. It is clear to see the value of such information.

CUMULATIVE TEMPERATURE STUDIES

Cumulative temperature profiles were calculated by the addition of the current day's temperature readings to the sum of the previous day's temperature readings. For example, on day 2 of a trial the readings gathered for each thermocouple or section were added to the readings of day 1 and on day 3 the daily readings were added to the summed readings of days 1 and 2 and so forth. Cumulative temperatures are a function of daily windrow temperature readings and the length of heating, thereby allowing different parts of a windrow or varying feedstocks to be compared (Flynn and Wood, 1996).

Figures 31 & 32 show daily mean cumulative windrow temperatures by layer, minus the cumulative ambient temperature for field trial 1 (winter) and 2 (summer) over similar time periods, as previous normal temperature plots. The number of data points varied between cumulative plots and therefore the graphs are employed to indicate the general pattern of temperature trends. There were clear differences between the experimental trials. The second trial showed a far greater cumulative temperature range than the first trial by day 38. Field trial 1 displayed a sigmoid shaped plot whilst trial 2 a linear form. There was, over the first 3 days, a quite rapid increase in cumulative temperature in trial 1, followed by a period of fairly low activity before a rapid increase and then a plateau (cf. normal temperature plots). The second trial showed a fairly continuous steady rise in cumulative temperature over the trial period. The data support the hypothesis that the feedstocks of the second trial contained materials which resulted in greater heat production, coupled with more favourable weather conditions (reduced windspeed), which allowed prolonged elevated temperatures and thus, improved composting conditions (accepting that increased temperature results in faster degradation rates and more efficient pathogen reduction) than Field Trial 1. The results demonstrate, not only that the first trial's temperatures were in general lower than the second field trial, but that higher temperatures were short lived (hence, the s-shaped curve).

Examination of the data by layer reveals that in field trial 1, layer 1 to 4 plots were initially similar, with only layer 5 showing a difference. This was comparable to the data from the second field trial. After day 3, cumulative temperatures in layer 4 did not increase as fast as in Layers 1 to 3. In field trial 2, there was also a deviation at this time period, with layer 1 beginning to lessen in heat buildup. The data from both trials reflected over days 1 to 3 the widespread increase in temperature experienced by the feedstock after formation into a windrow, from ambient to at least mesophilic in nature.

Figure 31: Riverside composting Field Trial 1 (winter). Mean cumulative windrow temperatures (°C) minus cumulative ambient (air) temperature (°C) over Days 1 to 38 of the field trial at five windrow heights termed layers where thermocouples were positioned at varying depths.

Layer 1 indicates temperature readings from a height of 0.2m and depths of 0.5m, 1m and 2m. Layer 2 indicates temperature readings from a height of 0.5m and depths of 0.5m, 1m and 2m. Layer 3 indicates temperature readings from a height of 1m and depths of 0.5m and 1m. Layer 4 indicates temperature readings from a height of 1.5m and depths of 0.5m and 1m. Layer 5 indicates temperature readings from a height of 2m and a depth of 0.5m.

Insert figure is given to enable analysis of fine detail. Larger figure is given for direct comparison with data in Figure 32.

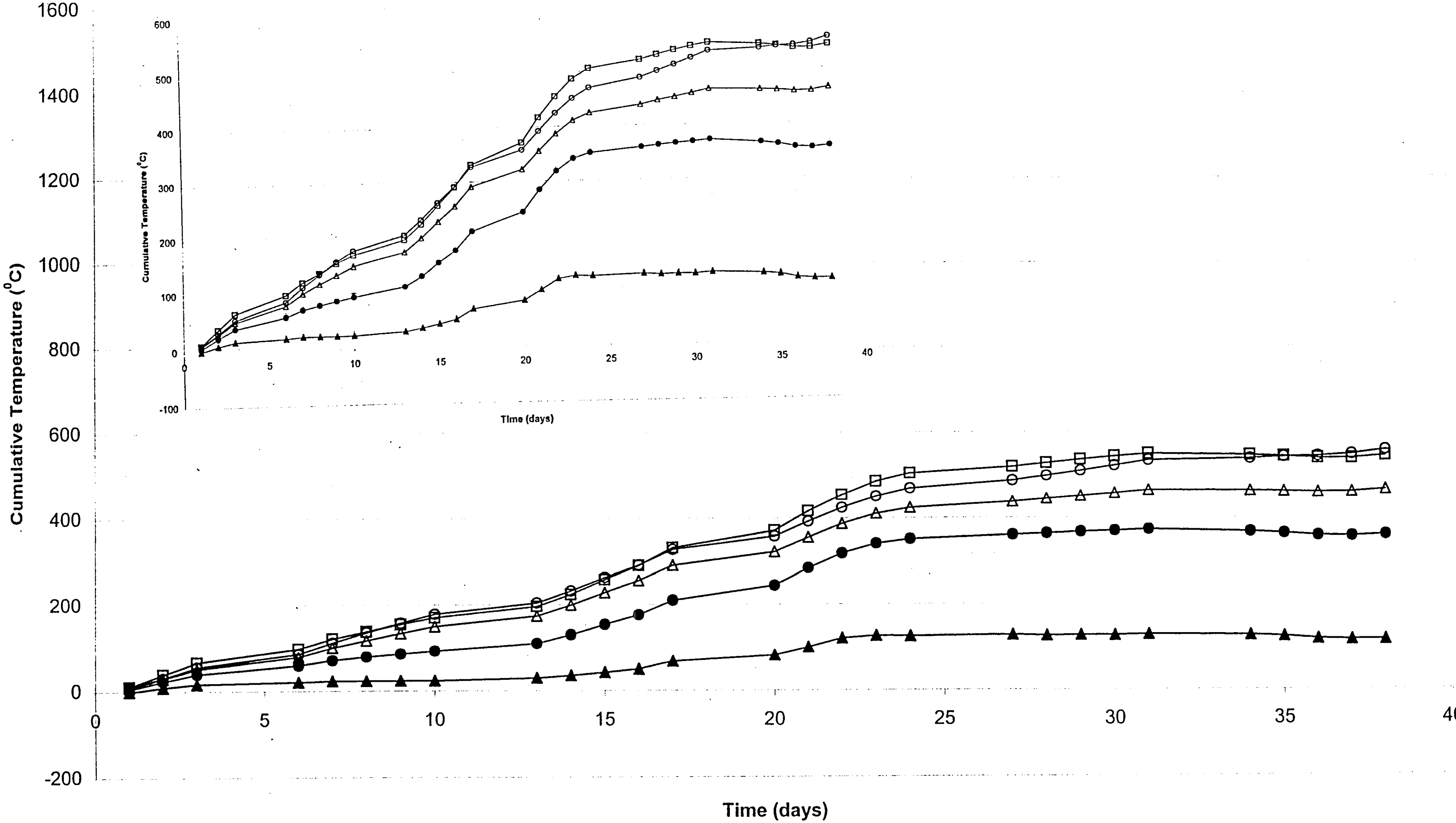
(○) Layer 1 mean cumulative temperatures (°C)

(△) Layer 2 mean cumulative temperatures (°C)

(□) Layer 3 mean cumulative temperatures (°C)

(●) Layer 4 mean cumulative temperatures (°C)

(▲) Layer 5 mean cumulative temperatures (°C)



Cumulative Temperature (⁰C)
1600
1400
1200
1000
800
600
400
200
0
-200
0
5
10
15
20
25
30
35
40
Time (days)
Cumulative Temperature (⁰C)
600
500
400
300
200
100
0
-100
Time (days)

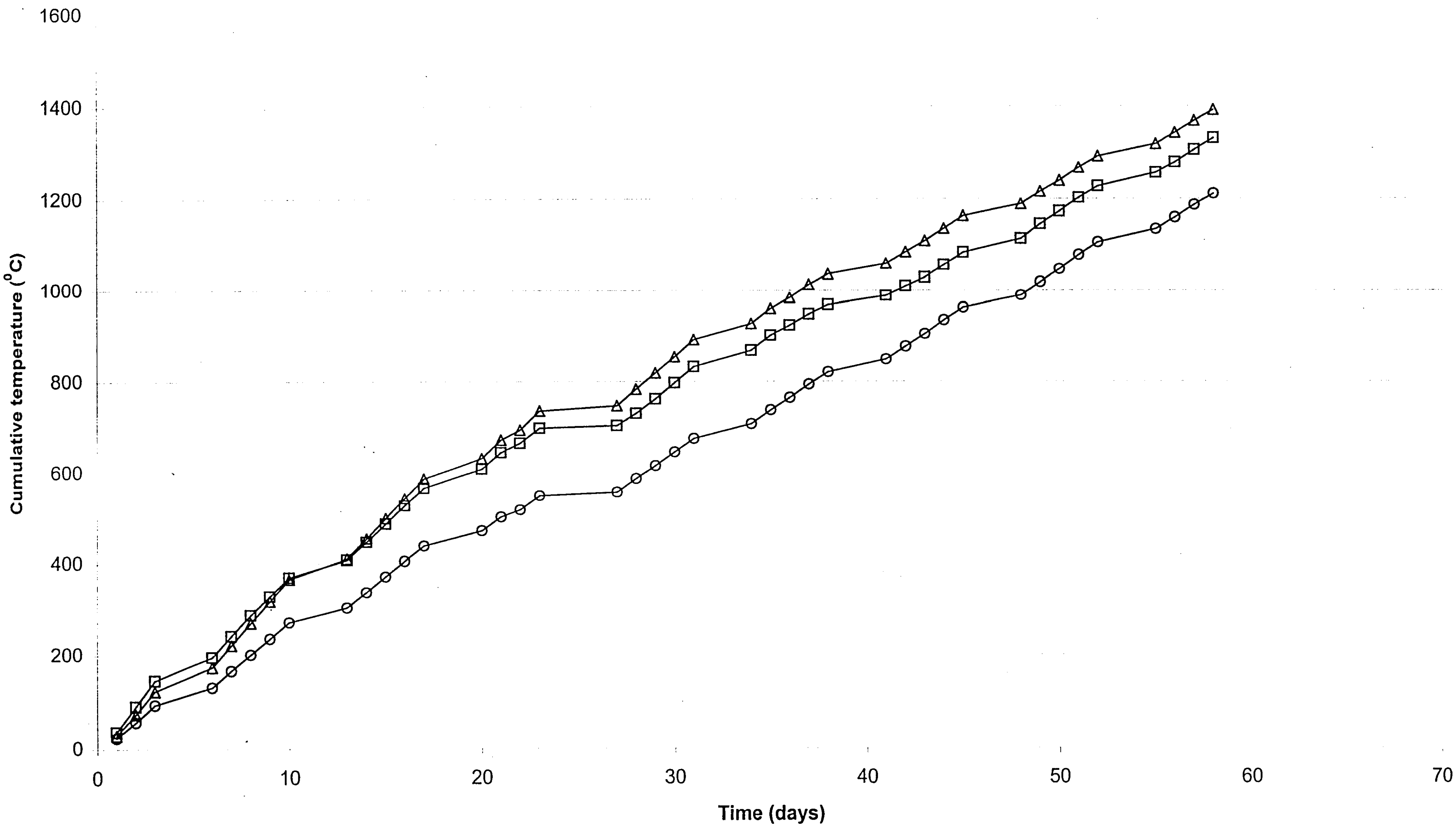
Figure 32: Riverside composting Field Trial 2 (summer). Mean cumulative windrow temperatures (°C) minus cumulative ambient (air) temperature (°C) over Days 1 to 58 of the field trial at three windrow heights termed layers where thermocouples were positioned at varying depths.

Layer 1 indicates temperature readings from a height of 0.3m and depths of 0.5m, 1m and 1.5m. Layer 2 indicates temperature readings from a height of 0.75m and depths of 0.5m and 1m. Layer 3 indicates temperature readings from a height of 1m and depths of 0.5m and 1m.

(○) Layer 1 mean cumulative temperatures (°C)

(△) Layer 2 mean cumulative temperatures (°C)

(□) Layer 3 mean cumulative temperatures (°C)



1600
1400
1200
1000
800
600
400
200
0
Cumulative temperature (^oC)
0
10
20
30
40
50
60
70
Time (days)

Layers 1 to 3 of the first field trial windrow continued to show relative proximity of profile for the following two weeks. The cumulative temperatures in layers 1 and 3 were essentially similar during the monitored period and this was also demonstrated in layers 1 and 2 of the second field trial. These layers were those which exhibited the greatest heat production, resulting in a combination of the highest temperatures and for the longest duration. These areas in both trials represented the zones of greatest composting activity in the long term. Of interest in trial 1 is that, although cumulative temperatures layer 2 were similar to layer 1 and 3 for much of the trial, they were always lower and these leveled off faster than in the other two layers. Layers 4 and 5 showed the generally expected lower levels of temperature accumulation. Layer 4 was quite active, but cumulative temperatures were considerably lower than in layers 1 and 3. One of the features of cumulative temperature monitoring can be observed from layer 4 data. During the mean daily temperature peak at around day 21, the temperatures exhibited in layer 4 were the second highest by mean layer temperatures (Figure 7). However, when these data were plotted in a cumulative temperature style, there was no major effect on the plots, (e.g. no change of series order). This is a benefit of cumulative temperature plots, in that short-term changes in temperature, for example a day or two of thermophilic temperatures within an otherwise mesophilic windrow, do not significantly affect the heat production trend. The important factor is that there must be a combination of high temperatures and sustainability for significant positive changes in the cumulative temperature trends of a windrow. This factor is equal to what is required for effective pathogen kill and therefore, cumulative temperature data is valuable as a process-monitoring tool to the commercial composter.

WEEKLY ANALYSIS OF PHYSICAL-CHEMICAL PARAMETERS

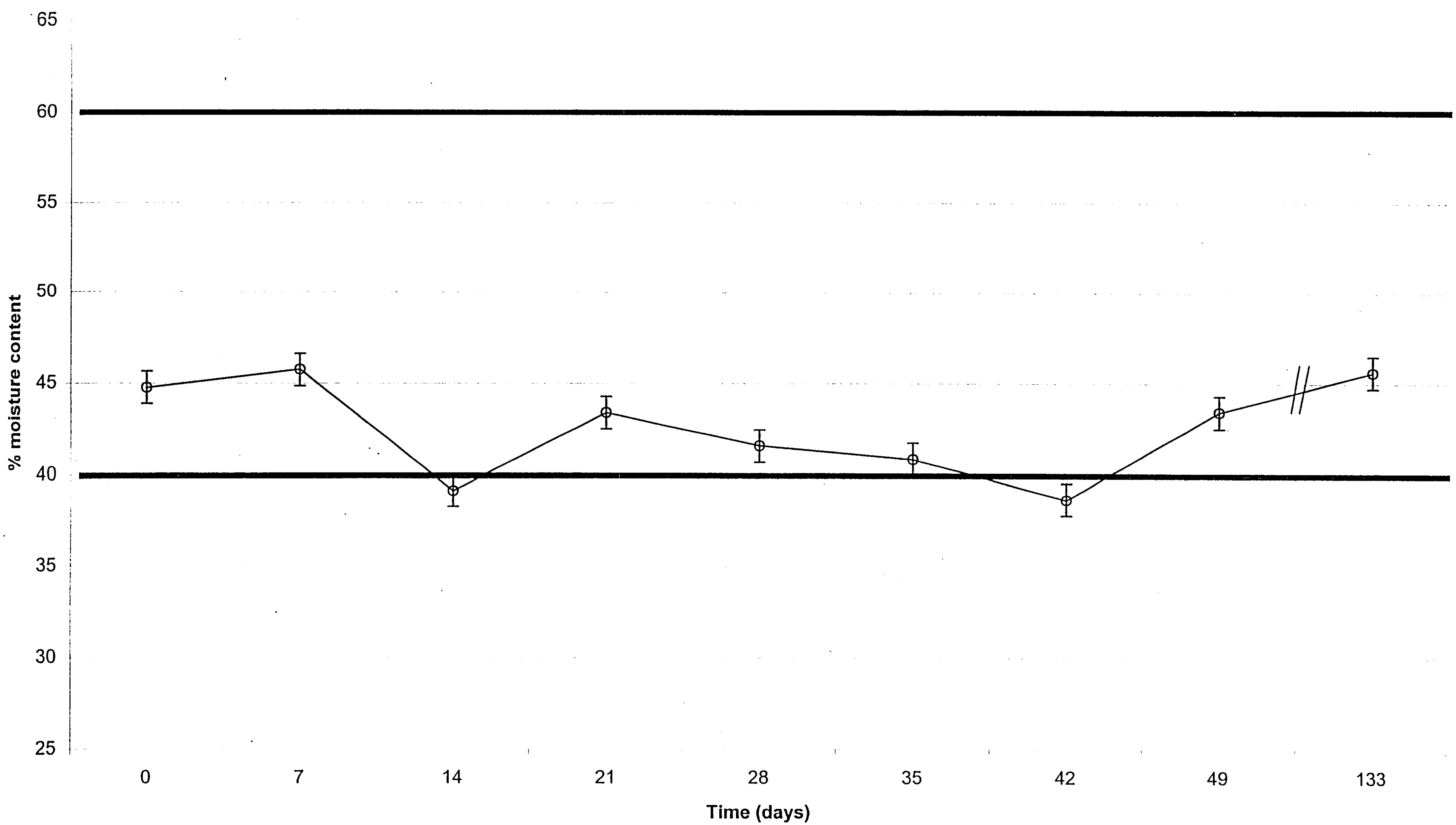
Both experimental field trial windrows (winter and summer established) were subject to a range of physical-chemical assays using samples collected from the windrows on a weekly basis, including pH, conductivity ($\mu S\ cm^{-1}$), % moisture content, % organic matter, bulk density (g l^{-1}), and selected heavy metal concentration *via* EDTA based extraction (mg kg^{-1} fresh weight). Material was manually collected with the aid of a small trowel and gloved hands from six points; three equally spaced along each side (lengthwise) of the windrow at approximately 1m high and between 0.3m and 0.5m below the surface. The assays were carried out using the methodologies outlined in the General Experimental Methods chapter of this study. These were done to complement the detailed monitoring of temperature within the windrow structures. During the composting process there is, in gross terms, a loss of organic matter (as it is decomposed) and an increase in the bulk density resulting from a change from a heterogeneous mix of waste (large irregular sized fragments) to a more homogenous blend of compost (small uniform sized fragments), due to the degradation and stabilization processes. A selection of physical-chemical data representing weekly-pooled mean figures from field trial 1 (winter) and 2 (summer)-collected samples are presented.

MOISTURE CONTENT AND ITS USE AS A PROCESS MONITOR

Recorded moisture levels (Figures 33 & 34) from the field trials were quite low and could be considered to be borderline in reference to other studies (Day and Shaw, 2001). However, the materials available as potential feedstocks in winter tend to be dry in nature (autumn leaves, woody cuttings etc) with a lesser amount of fresh green material normally procurable. In the case of the summer trial it was possible the dryness was caused by the low rainfall during the month preceding the establishment of the windrow and therefore reducing the water content of the waste materials. July is also the main time for summer vacation in Dundee, therefore materials on-site in early August could have been "*sitting around*" for slightly longer than is optimal. Although samples were taken from subsurface regions (0.3 to 0.5m below the windrow surface), temperature and windspeed data have demonstrated that these areas were subject to the direct effects of the wind such as cooling.

Figure 33: Riverside composting Field Trial 1 (winter). Weekly mean percentage (%) moisture content of windrow material from six subsurface (0.3-0.5m deep) bilateral sampling points. Heavy black horizontal lines show upper and lower recommended moisture levels (Day and Shaw, 2001; Rynk and Richard, 2001). Error bars represent the standard error of the data set.

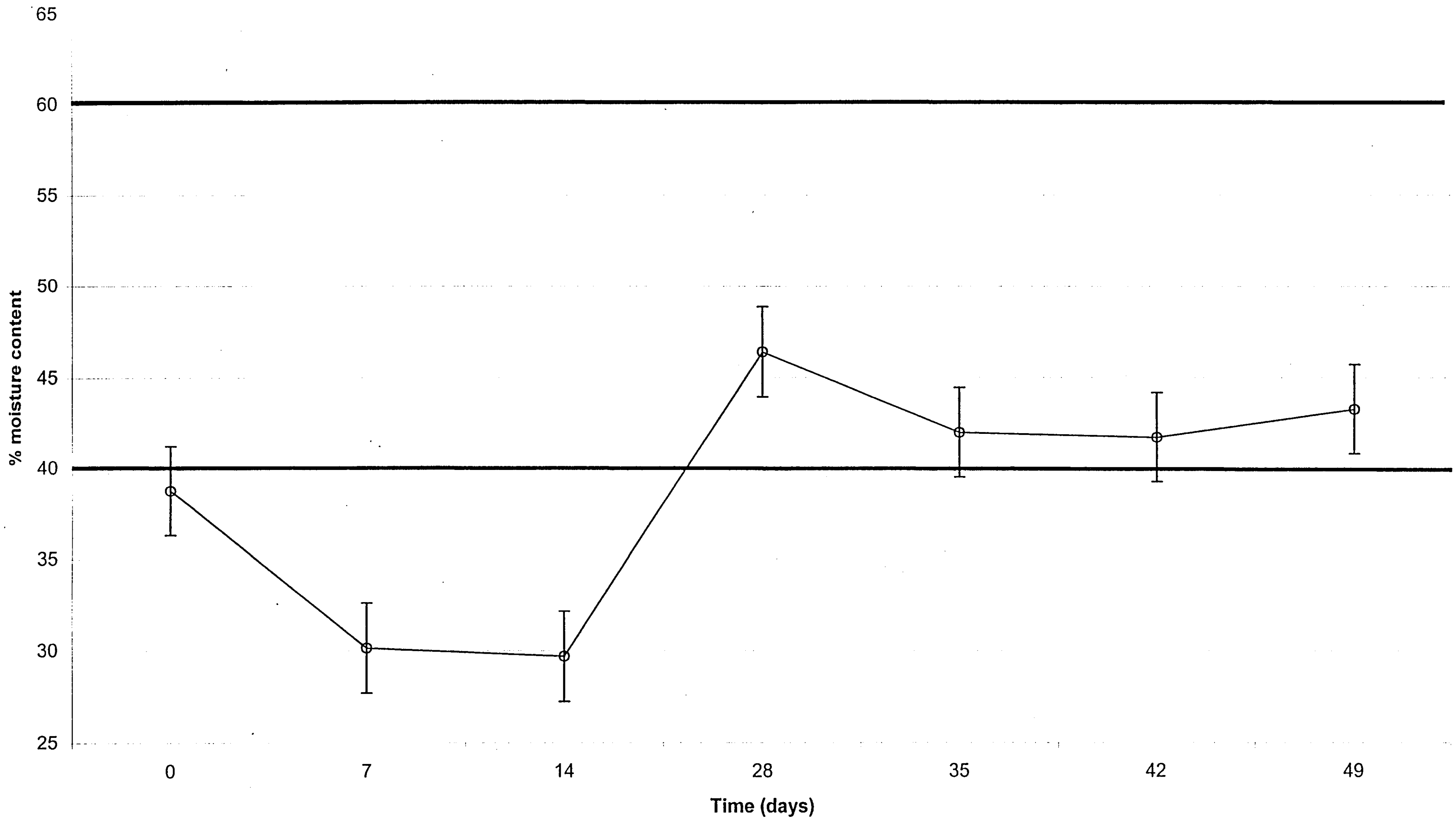
(○) Mean percentage moisture content of windrow material



65
60
55
50
45
40
35
30
25
% moisture content
0
7
14
21
28
35
42
49
133
Time (days)

Figure 34: Riverside composting Field Trial 2 (summer). Weekly mean percentage (%) moisture content of windrow material from six subsurface (0.3-0.5m deep) bilateral sampling points. Heavy black horizontal lines show upper and lower recommended moisture levels (Day and Shaw, 2001; Rynk and Richard, 2001). Error bars represent the standard error of the data set.

(O) Mean percentage moisture content of windrow material


65
60
55
50
45
40
35
30
25
% moisture content
0
7
14
28
35
42
49
Time (days)

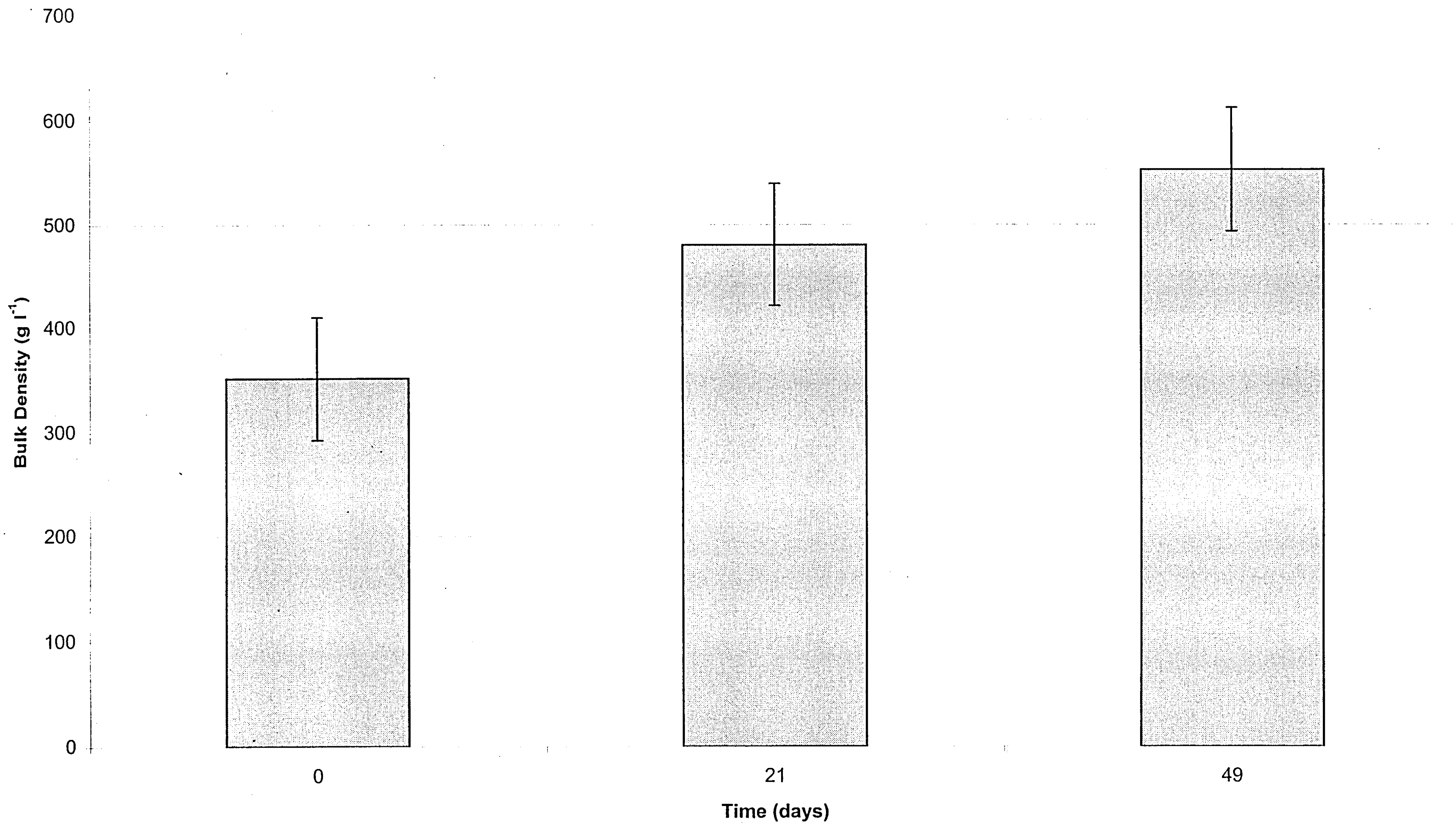
Thus it is also reasonable to suggest that these zones were subjected to the drying effects of the wind. The loss of water by evaporation possible at these regions could also control the moisture levels here as well as the drying effects on internal heat production. Monthly rainfall data from the nearby (approximately 10 miles distant) RAF Leuchars airbase weather station (http://www.met.rdg.ac.uk/) showed that rainfall was quite low during the period of the trial 1 (64mm total rain during the first 8 weeks or 70% of the expected average), limiting the potential increase that the outer-regions of any windrow (regardless of the quality of windrow design) would expect to see. Similar information for the trial 2 period revealed low rainfall during the first fortnight and a mean ambient temperature of around 15°C (and widespread internal heat, therefore significant microbial activity) resulting in the loss of moisture from the material sampled. Increased levels of rain after this period (126mm total rain or 207% of the expected level) clearly affected the water content of the more peripheral regions of the windrow structure resulting in the increases in moisture recorded during the later period. Moisture is critical to microbial life processes and therefore activity within the windrow, and levels outside a range of approximately 40% to 60% are considered to be detrimental to the composting process (Rynk and Richard, 2001). It is therefore common for the measurement of the level of moisture within a composting system to be considered a parameter by which the process may be monitored. However, removing samples for moisture analysis results in both the disturbance and destruction of the composting unit. The intertwining and compressive nature of the feedstocks in a typical active windrow makes entry to the core regions and removal of samples from the windrow a difficult and time-consuming task. The data presented in this study show subsurface moisture levels. However, these do not necessarily reflect the levels within the deepest core regions where the most active composting processes occurred. Material from such regions is not in a practical sense obtainable. Trial temperature data suggests that thermophilic temperatures were recorded and sustained, especially in field trial 2 within the core areas of the windrows, indicating that moisture was not a limiting factor (in a general sense, for individual areas could have been moisture limited and been the cause of the reduced temperatures experienced in certain inner areas of the windrows). The similarity between recorded moisture contents in both trials, compared to the divergent temperature trends during the latter time periods of the trials indicate the lack of bearing these subsurface moisture measurements have on the state on the general composting process. The difficulty of obtaining representative samples and apparent lack of relationship between moisture content and general windrow temperature trends, automatically limit the value and practicality of the technique of moisture content assessment for the routine monitoring of the windrow composting process. It is suggested that moisture analysis is most suitable for the following situations; freshly shredded feedstocks (initial assessment and / or adjustment), during the process of windrow reformation after turning (especially if thermophilic temperature development is problematic) and final product profiling. Moisture analysis, which should be linked to temperature assessment, is best suited to situations where a windrow or perhaps part of the windrow is experiencing difficulties and the assessment of moisture content and its rectification, if too wet or dry, can be performed.

BULK DENSITY CHANGES WITHIN SAMPLES OF FEEDSTOCKS

Samples of field trial 2 material were assessed for changes in bulk density (mass in a given volume) over selected time intervals (freshly shredded material, three-week-old material and seven-week-old) and the data are presented in Figure 35. There was a clear increase in the bulk density of the sampled material. The data it can be noted do not reflect any changes in the overall density and level of compaction of the windrow itself, but rather changes in the nature of the sampled material. An increase in the density of the feedstocks is an indication of a reduction in particle size and heterogeneity and a move toward a finer uniform material, thus it is a measurement of the level of decomposition within the feedstocks.

Figure 35: Riverside composting Field Trial 2 (summer). Selected mean bulk density measurements (g l^{-1}) of windrow material from six subsurface (0.3m-0.5m deep) bilateral sampling points over time (days). Error bars represent the standard error of the data set.

(■) Mean bulk density (g l^{-1}) of windrow material.



700
600
500
400
300
200
100
0
Bulk Density (g l-1)
0
21
49
Time (days)

The largest changes occurred during the first three weeks of the trial, with an increase of 128.35g l^{-1} compared with an increase of 72g l^{-1} between weeks 3 and 7 of the trial. Bulk density increased from a starting value of 351g l^{-1} to a final value of 552g l^{-1}. This confirms that the greatest or fastest level of microbial degradation occurred during the first 3 weeks of the trial, when temperatures with the windrow in gross terms were hottest. It can be noted that the mean overall windrow temperature plot showed a marked decrease in temperature after approximately three weeks. These data suggest that this slowed the rate of decomposition of material and hence increase in bulk density of the material, in the regions of the windrow removed for sampling.

ORGANIC MATTER CHANGES DURING THE COMPOSTING PROCESS

The increase in bulk density can be linked to a decrease in the organic matter content of the sampled material. Microbial decomposition results in the loss of carbon (organic matter) as carbon dioxide to the atmosphere and also a percentage is recycled as microbial biomass. The remainder is converted into more stable forms (humus) by microbiological action and is the basis of the soil improvement characteristics of compost. A downward trend in organic matter content can be observed in data from field trial 2 (Figure 36), with a starting value of 59.5%, after 4 weeks a value of 50% and after 7 weeks a value of 46.7% organic matter, representing an overall loss of 12.8%. The data again suggest a slowing of degradation in the latter stages of the monitored period.

Organic matter data from field trial 1 also shows a downward trend (Figure 37). The higher starting value of 82.6% (compared with 59.5% for field trial 2) is indicative of the woody, high carbon to low nitrogen ratio, material typically available for windrow construction at this time of year (and poorer overall performance in temperature terms of this windrow). As in field trial 2 there was some variation in the values over the timespan, but there was a clear reduction in the organic matter content over 19 weeks from 82.6% to 58.4%.

Figure 36: Riverside composting Field Trial 2 (summer). Weekly mean percentage (%) organic matter content of windrow material from six subsurface (0.3m-0.5m deep) bilateral sampling points over time. Error bars represent the standard error of the data set.

(○) Mean % organic matter content.

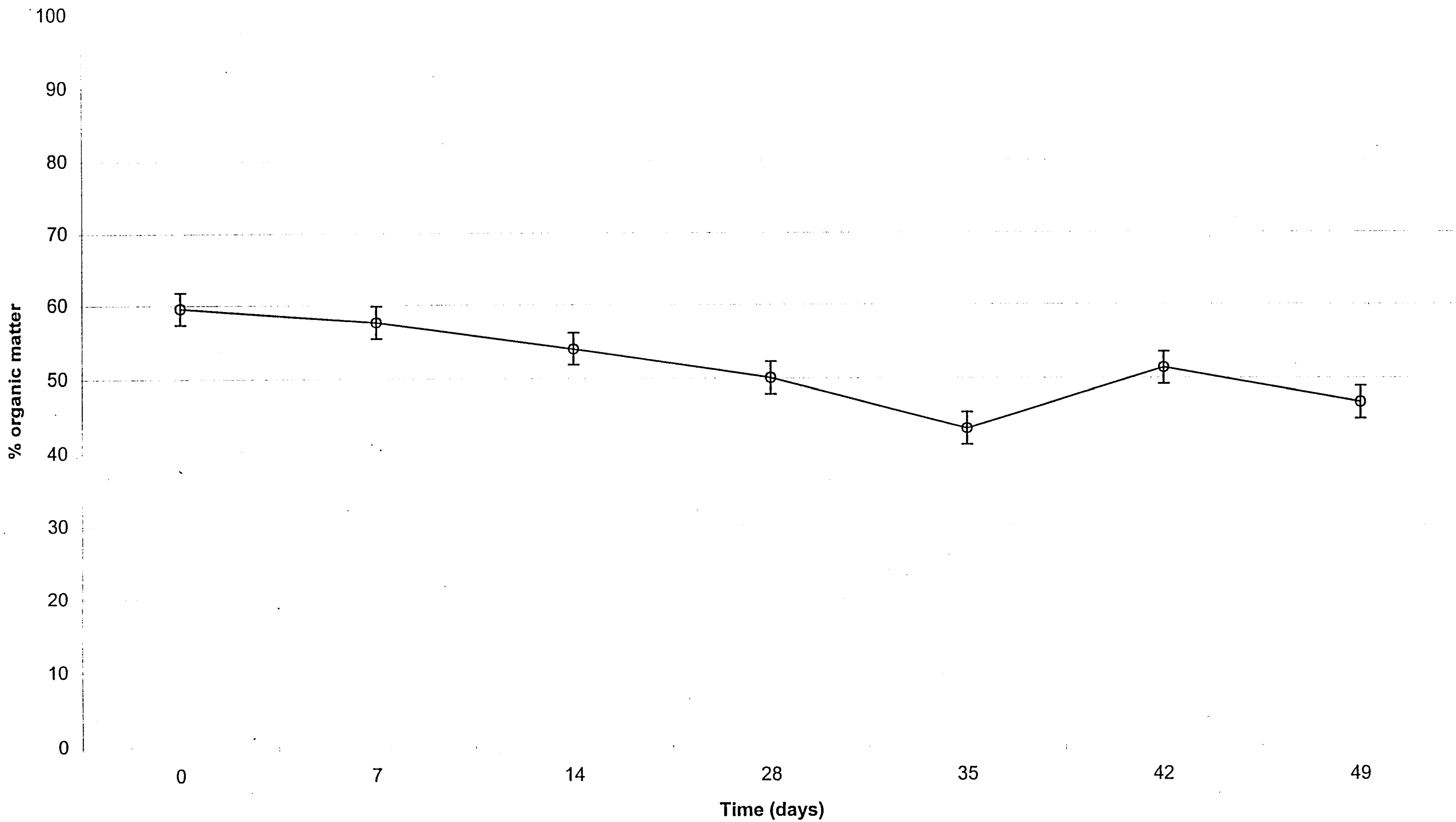
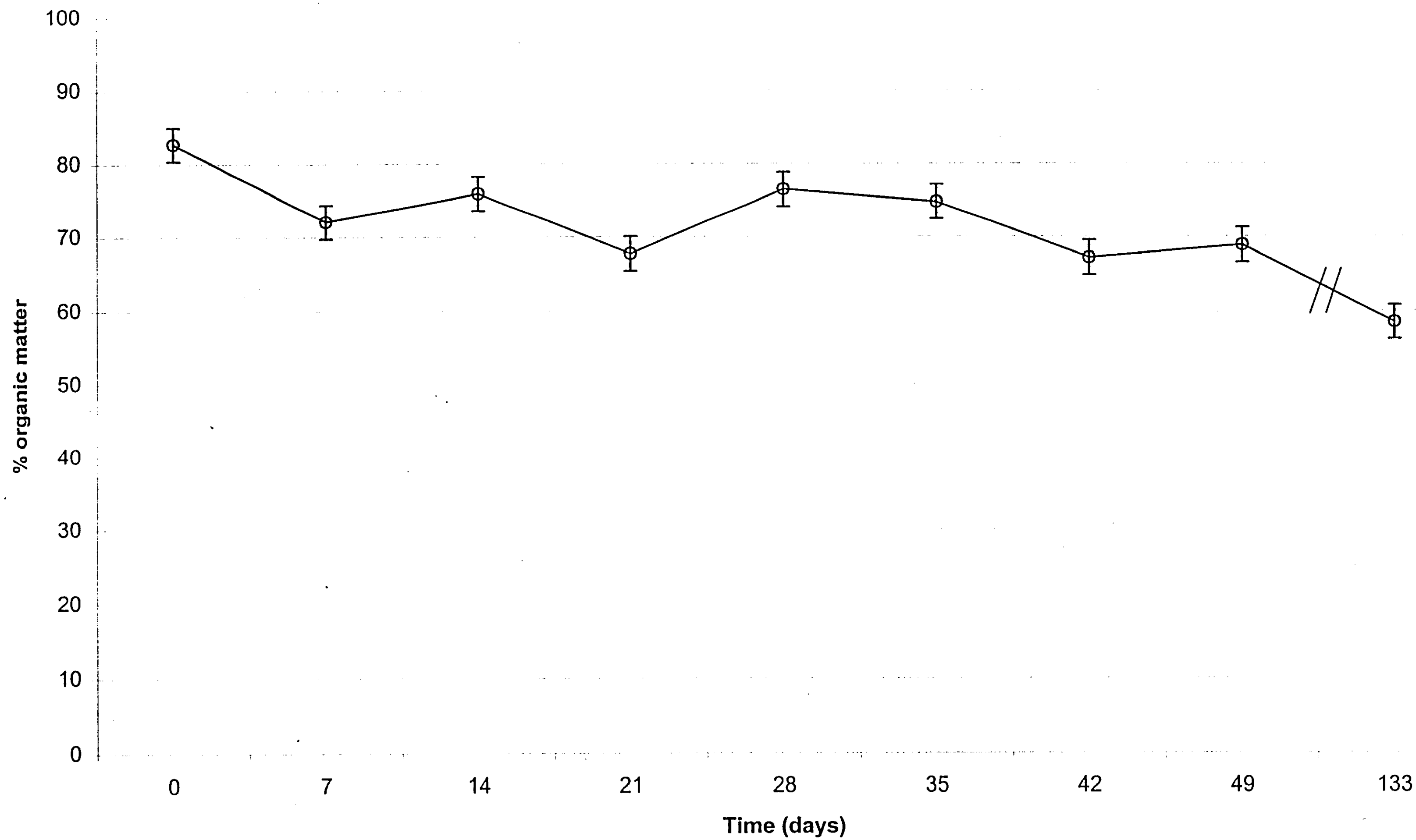

100
90
80
70
60
50
40
30
20
10
0
% organic matter
0
7
14
28
35
42
49
Time (days)

Figure 37: Riverside composting Field Trial 1 (winter). Weekly mean percentage (%) organic matter content of windrow material from six subsurface (0.3m-0.5m deep) bilateral sampling points over time. Error bars represent the standard error of the data set.

(O) Mean % organic matter content.



100
90
80
70
60
50
40
30
20
10
0
% organic matter
0
7
14
21
28
35
42
49
133
Time (days)

This is clear evidence that decomposition was occurring even in the less central areas used for sample collection and assessment. This was true in both experimental windrows. The data from this study show that measurement of the organic matter content of windrow material is a valid method for the long-term assessment of the level of decomposition and eventual stabilization. The variation in the data seen in both trials on a weekly basis may limit its use as a short time process monitor. The variation was in part due to the inherent fluctuations in the nature of the samples on a weekly basis, which may by chance have contained a higher percentage of woody materials one-week than another. This variation may be reduced by the development of a novel sampling methodology. Additionally, it is affected by the changes in the nature of the feedstocks over the course of the process. There is an initial rapid utilization of easily degradable organic matter by the microbial population, resulting in a relatively rapid and steady decline in organic matter content (and an associated increase in bulk density) as revealed by the trial data. After approximately 4 weeks (in this study), the easily degradable nutrient sources are largely used up, leaving the more difficult to degrade material, (e.g. woody lignin rich items) (cf. the temperature decline during this period). This concentration effect and differential degradation (possibly also the build of microbial biomass) would result in increased levels of organic matter in the feedstocks and a slow rate of breakdown, as evidenced in the latter stages of the trial data.

SURVEYING OF FIELD TRIAL WINDROWS

The winter (Field Trial 1) windrow was subjected to surveying *via* electronic tacheometry at two time points, establishment and after 4 weeks. This allowed both the shape, (i.e. the contours) of the structure to be determined and also the volume of the windrow to be calculated (Figures 38a & b, Table 3). The use of two surveys allowed any changes in these features to be assessed. Analysis of the data show that the winter windrow had an initial volume of 50.5m^3, and that after a period of 4 weeks the volume of the windrow was

Figure 38a: Riverside Composting Field Trial 1 (winter) Contour plot of windrow structure at establishment derived *via* electronic tacheometry. Contour line: m above standard datum. Contour interval: 0.2m. Scale: 1:50.

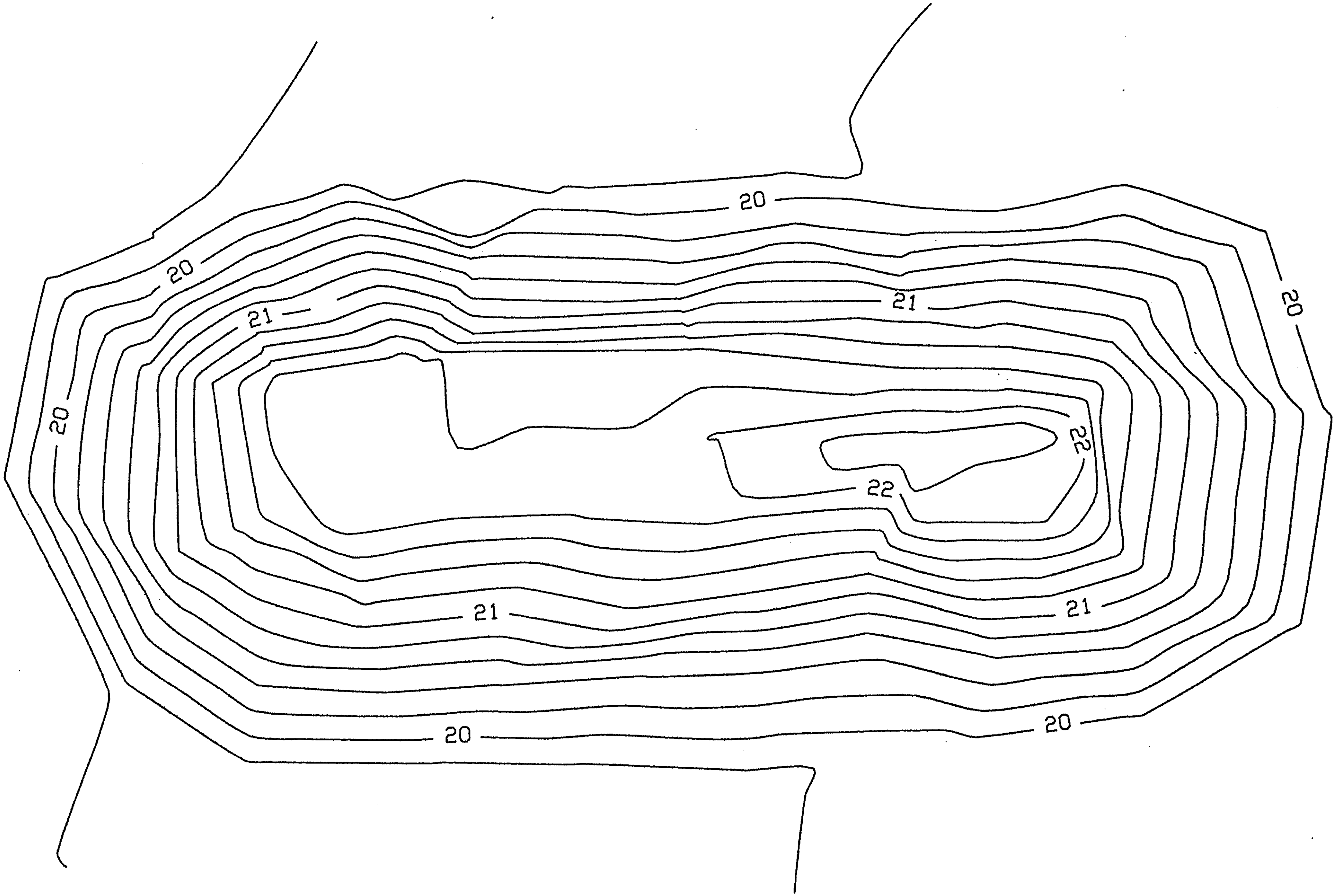

20
20
20
20
20
20
21
21
21
21
22
22

Figure 38b: Riverside Composting Field Trial 1 (winter) Contour plot of windrow structure at 4 weeks derived *via* electronic tacheometry. Contour line: m above standard datum. Contour interval: 0.2m. Scale 1:50.

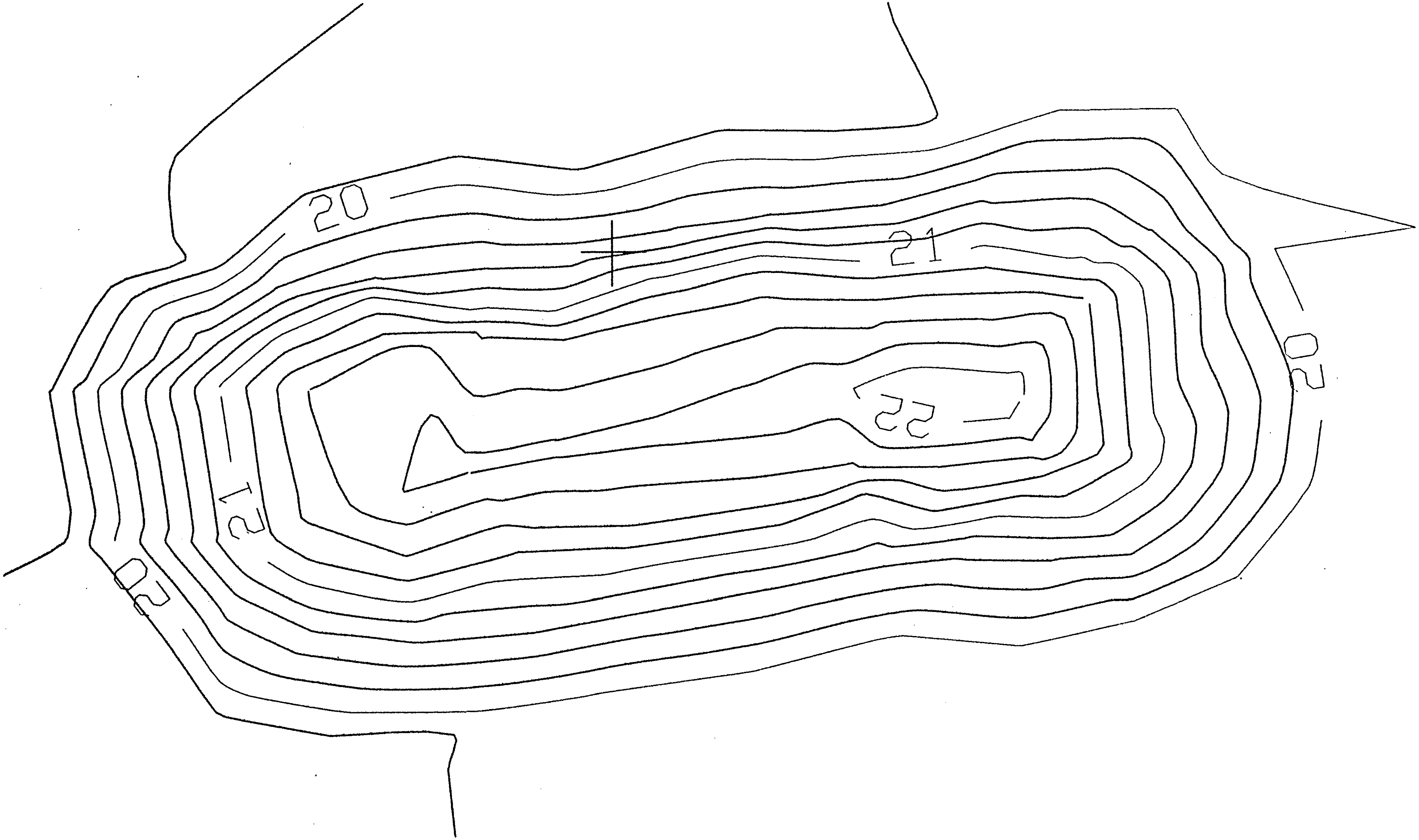

20
21
22
21
20
20

Table 3: Electronic Tacheometry Survey of Field Trial 1 (winter) Windrow. Volume (m^3) determination of windrow at establishment and after 4 weeks. Contour line m above standard datum. Contour interval 0.2m

Contour line (m S.D)	Volume (m^3) at establishment	Volume (m^3) at 4 weeks
20.0	9.3	9.58
20.2	8.1	8.22
20.4	7.1	6.97
20.6	6.1	5.91
20.8	5.3	4.96
21.0	4.4	40.9
21.2	3.7	3.25
21.4	3.0	2.32
21.6	2.1	1.22
21.8	1.1	0.38
22.0	0.3	0.06
22.2	0.1	0
Total Volume (m^3)	50.5	46.96

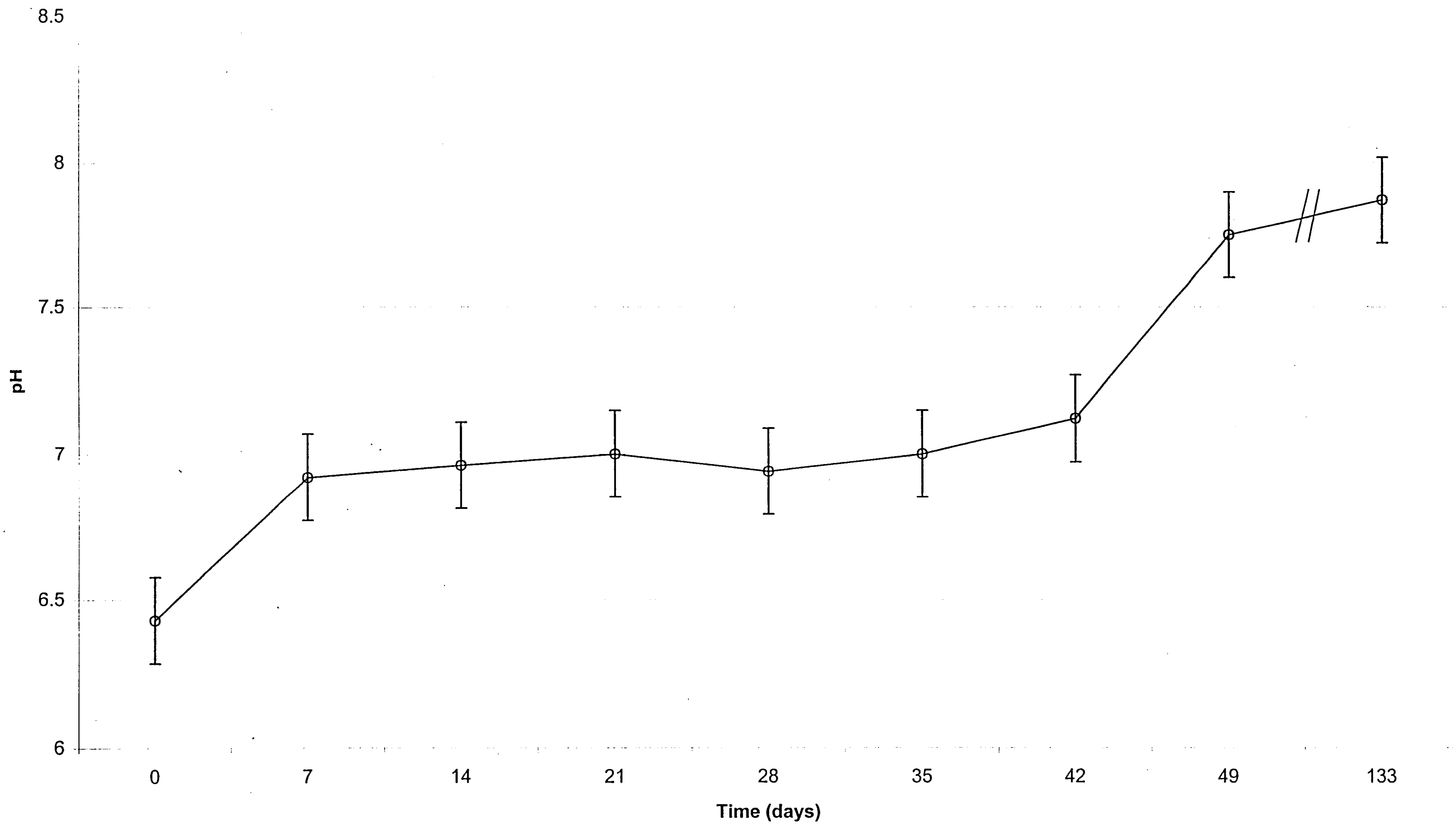
46.9m^3, a reduction of 7.12% in volume. This can be compared to an organic matter content loss of 7.38% over the same period (Figure 37). The results suggest than the loss in volume of the windrow was due in part to a reduction in the levels of organic matter within the structure. It is suggested that much of this organic matter was lost to the atmosphere as CO_2 during microbial metabolism. The surveying of the windrow also revealed the process of windrow slumping (i.e. a tendency for the upper parts of a windrow to collapse downwards under their own weight over time). The survey data indicated that the volume of the lowest 0.2m of the windrow increased during the time period whilst the upper regions decreased. This meant that the base of the windrow became broader and more compressed as composting progressed. This suggests that the lower regions would become progressively less suitable for aerobic microbial activity as increased compression and *in situ* bulk density would reduce the internal voids present for the free movement of moisture and gas exchange. Such compressional activity would also account in part for the reduction in volume during the first 4 weeks of composting. Turning of the windrow would be essential to maintain optimal composting conditions. Temperature data (Figure 9) showed a general downward pattern at around this time. The results of the surveying experiment demonstrated that such a technique is capable of recording the decompositional progress of a typical green waste windrow. The data showed a potential link between the reduction in organic matter content and loss in windrow volume during a 4-week period of active composting. The technical complexity of the surveying technique, and specialist equipment and software used, effectively inhibit the employment of this assessment methodology on a routine basis on a commercial composting site. However, as a research tool, surveying *via* electronic tacheometry has been shown, in this study, to be a practical and useful means of assessing the structural form and related changes in a windrow, as well as the rate of the composting process.

CHANGES AND TRENDS IN pH

The pH of collected samples from both experimental windrows was assessed on a weekly basis. Data from both trials (Figure 39 & 40) show an increase in the value of pH over time. This is confirmatory with other worker's findings, which describe a raise from around neutrality to a more basic final figure (deBertoldi *et al*, 1983; Michel and Reddy, 1996). A pH of between pH7.5 to 8.5 is typical of many green waste derived composts, and earlier studies of Dundee City Council's Discovery Compost, that investigated final product quality (Gartland *et al,* 1997; Irvine, 1999), revealed values in this range. The pH of the feedstocks is dependent on their composition and therefore, may vary seasonally. Changes over the course of the composting process are due to microbially produced metabolic by-products and alterations to facilitate the uptake or removal of certain nutrients. The data from these studies showed that after an initial rapid rise to around pH 7 (see later for more detail on field trial 2) there was a period of relative stability. Both trials showed a period of sudden pH increase, at week 7 for field trial 1 (pH 7.12 to 7.75) and week 5 for field trial 2 (pH 7.44 to 7.78). This is strongly suggestive of a dramatic change in the environment of the windrow at these time intervals and a related change in the types of microorganism present (a pH based succession event). The difference in timing would indicate that this change was related to the level of decomposition of the feedstocks (i.e. progress of the composting process) and, as the temperature data suggest a more productive / faster composting process in the second trial, this would explain why the sudden increase event occurred earlier in this trial. The data show that the increase in pH during the composting of urban green waste within open windrows does not appear to be essentially linear, but subject to sudden dramatic and microbially controlled rises before final stabilization.

Figure 39: Riverside composting Field Trial 1 (winter). Weekly mean pH values of windrow material from six subsurface (0.3m-0.5m deep) bilateral sampling points. Error bars represent the standard error of the data set.

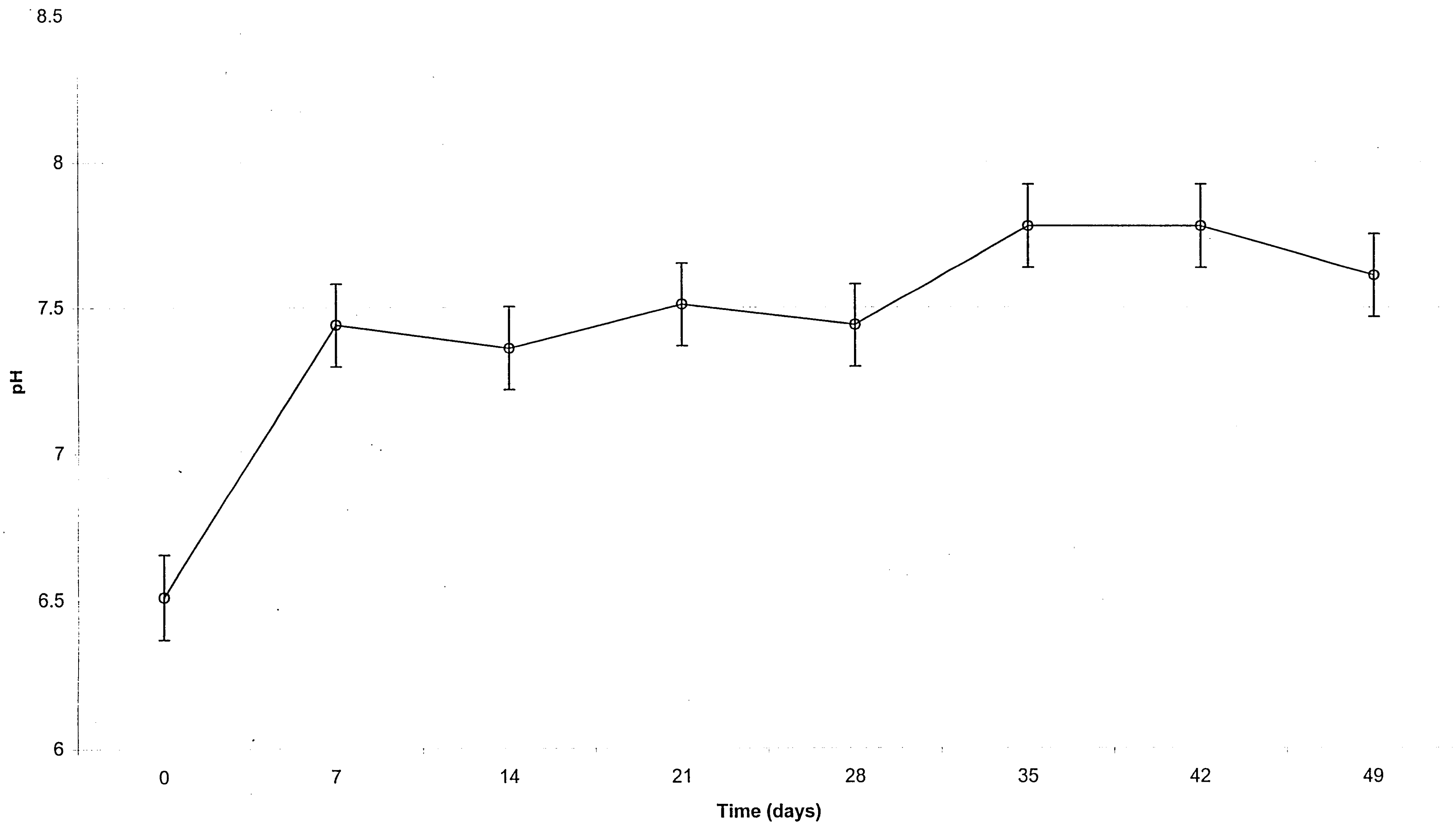
(O) Mean pH value of windrow material.



8.5
8
7.5
7
6.5
6
pH
0
7
14
21
28
35
42
49
133
Time (days)

Figure 40: Riverside composting Field Trial 2 (summer). Weekly mean pH values of windrow material from six subsurface (0.3m-0.5m deep) bilateral sampling points. Error bars represent the standard error of the data set.

(O) Mean pH value of windrow material.

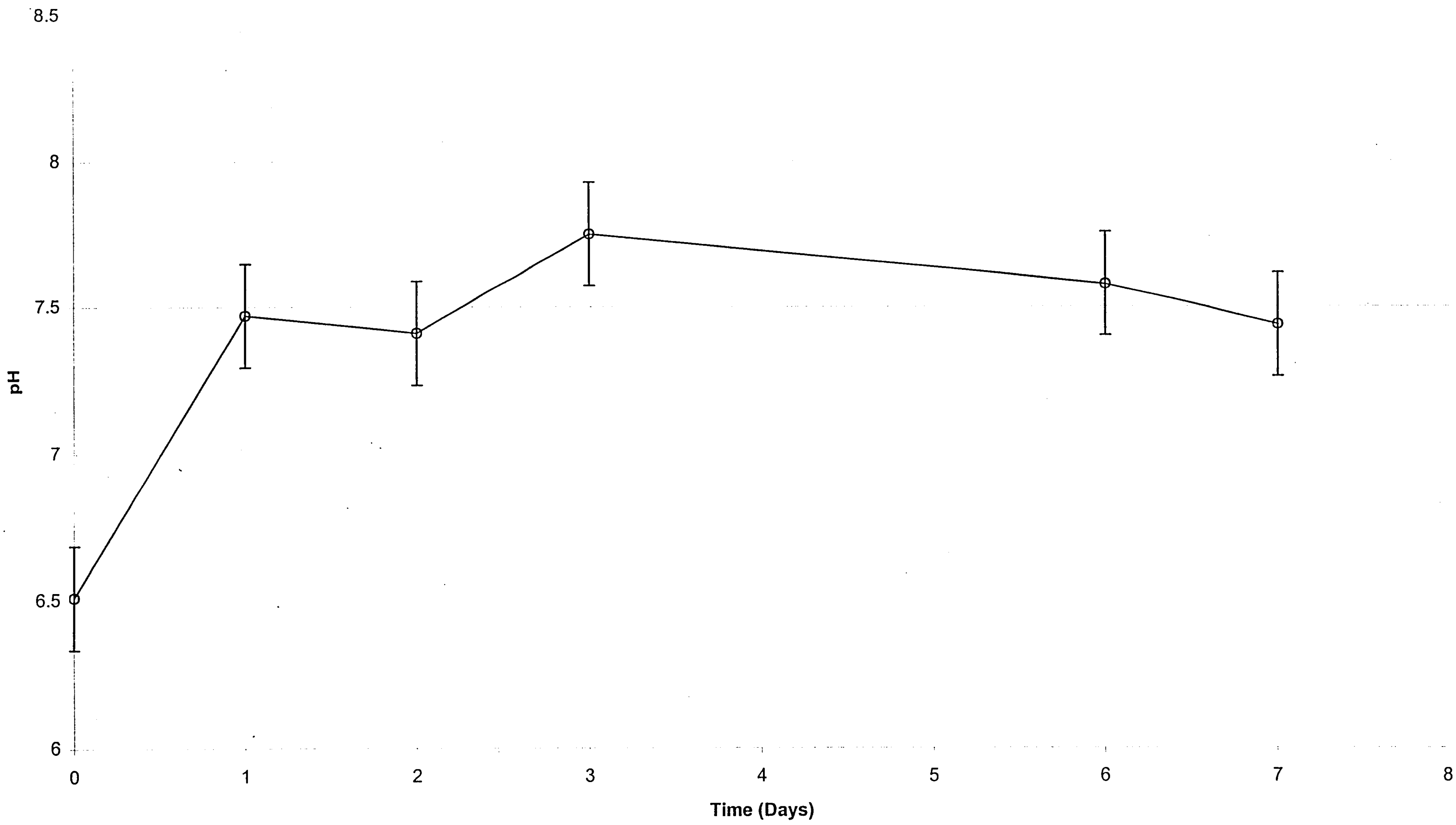

8.5
8
7.5
7
6.5
6
pH
0
7
14
21
28
35
42
49
Time (days)

CHANGES IN pH OVER FIRST WEEK WITHIN SUMMMER WINDROW

Samples were removed on the day of establishment (day 0), the following three days and finally days 6 and 7, to identify the changes in pH occurring within the feedstocks following establishment of a windrow (Figure 41). Research has shown that the initial breakdown of wastes often results in the production of sugar-acids, which reduce the pH of the windrow environment before other microbial processes cause a rise in general pH values (Day and Shaw, 2001). This experiment aimed to record this event and any other changes, which might occur during this time period. The results indicated that the production of such sugar acids may have already occurred prior to the establishment of the windrow, with a pH value of 6.51 recorded on Day 0. This was not unexpected, as microbial degradation of plant material starts as soon as the plant dies, and waste entering a commercial composting site may sit for several days before processing, thereby allowing uncontrolled degradation to occur. However, it is clear that this pre-windrow-establishment activity was different from in-windrow activity, for there was a dramatic rise in pH from day 0 to day 1, from pH 6.51 to pH 7.47 over 24 hours. The upward trend in pH continued to at least day 3 (pH 7.75) (no record over the subsequent weekend) before a slight reduction back to pH 7.44 at day 7. The data indicated that microbial activity and / or physical conditions, found only within a windrow situation, caused this rapid change in pH of the waste materials. The most obvious difference between non-windrow and windrow environments is temperature. Material prior to shredding is essentially at ambient or, slightly above, temperatures, and any decay at this time is carried out by low temperature microorganisms at a slow rate. After shredding and windrow formation, the enhanced conditions allow a rapid proliferation of microorganisms and an increase in metabolism and hence heat production, allowing a shift to high temperature microbes (Stenbro-Olsen, 1998). Temperature data from field trial 2 showed that by day 1 there were wide spread thermophilic temperatures, peaking in the mid 60°C range, which continued to increase, peaking by day 3 at approximately 80°C, after which there was some decline.

Figure 41: Riverside composting Field Trial 2 (summer). Changes in mean pH values (samples taken from six subsurface (0.3m-0.5m deep) bilateral sampling points) over the first week following establishment of the field trial windrow. Error bars represent the standard error of the data set.

(○) Mean pH value of windrow material.


8.5
8
7.5
7
6.5
6
pH
0
1
2
3
4
5
6
7
8
Time (Days)

This strongly suggests that the changes in pH observed over the first week of composting were linked to the temperature profile during this time and by association, the microorganisms active then. These microorganisms were clearly producing chemical changes within the feedstocks that resulted in the increasing pH trend recorded. The data did not indicate a decrease in pH through the production of sugar-acids as other research has suggested, but rather a very rapid increase during the first week. This indicates that the degradation of specific substrates to produce sugar-acids is a feature of mesophilic microbial activity and is likely to have occurred prior to shredding and windrow formation, for as soon as thermophilic conditions were present microbial activity switched to a type that resulted in pH increase.

CONDUCTIVITY MEASUREMENTS

Conductivity assesses the levels of soluble salts within a sample. It is an expression of the ability of an aqueous solution to carry an electric current. It depends on the presence of ions, their concentration, valency, mobility and the temperature. Solutions of most inorganic acids, bases and salts are relatively good conductors. Analysis was carried out on weekly samples from both trials in order to assess for trends during the composting process (Figure 42). Values from field trial 1 showed little change over the monitored period, and ranged from approximately 400 to 500μS cm^{-1}. Field trial 2 results indicated a much more elevated level of conductivity initially (1991.48μS cm^{-1}) before a downward trend over time with a final figure of 1032.41μS cm^{-1}. The differences between the first and second trials presumably reflected the seasonal variation in the type and quality of the feedstocks. The more diverse and greener feedstocks available during the summer months are more nutrient rich and therefore, resulted in the enhanced level of conductivity noted here. The changes in conductivity in both trials appeared to be directly linked to changes in moisture content and thereby, ultimately rainfall (Figure 43). In general terms, drier materials were correlated with an elevation in conductivity (a concentration effect). The lack of notable

Figure 42: Riverside composting Field Trials 1 (winter) and 2 (summer). Weekly mean conductivity values (μS cm^{-1}) of windrow material from six subsurface (0.3m-0.5m deep) bilateral sampling points. Error bars represent the standard error of the data sets.

(○) Mean conductivity values Field Trial 1 (winter)

(△) Mean conductivity values Field Trial 2 (summer)

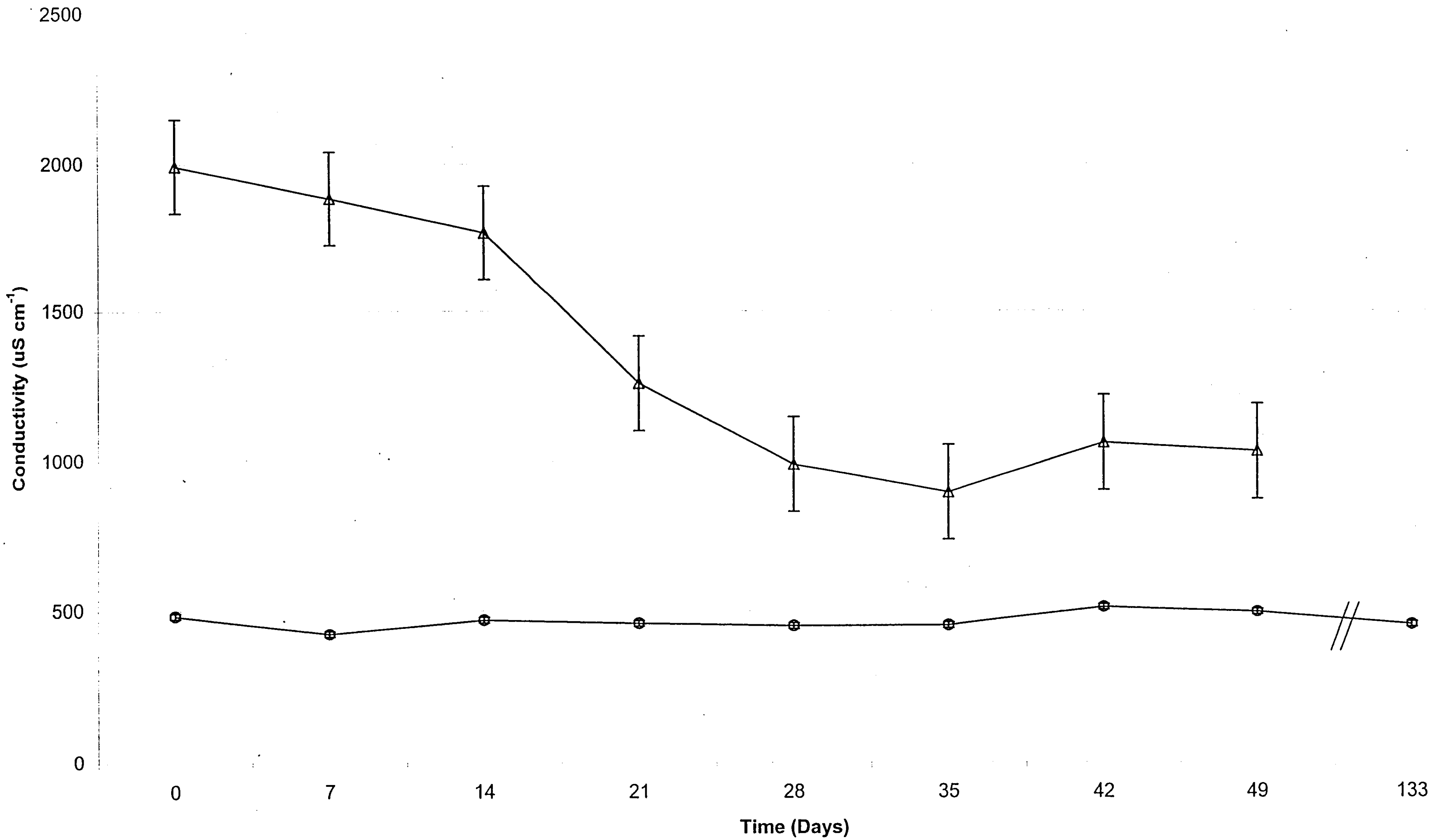

2500
2000
1500
1000
500
0
Conductivity (uS cm-1)
0
7
14
21
28
35
42
49
133
Time (Days)

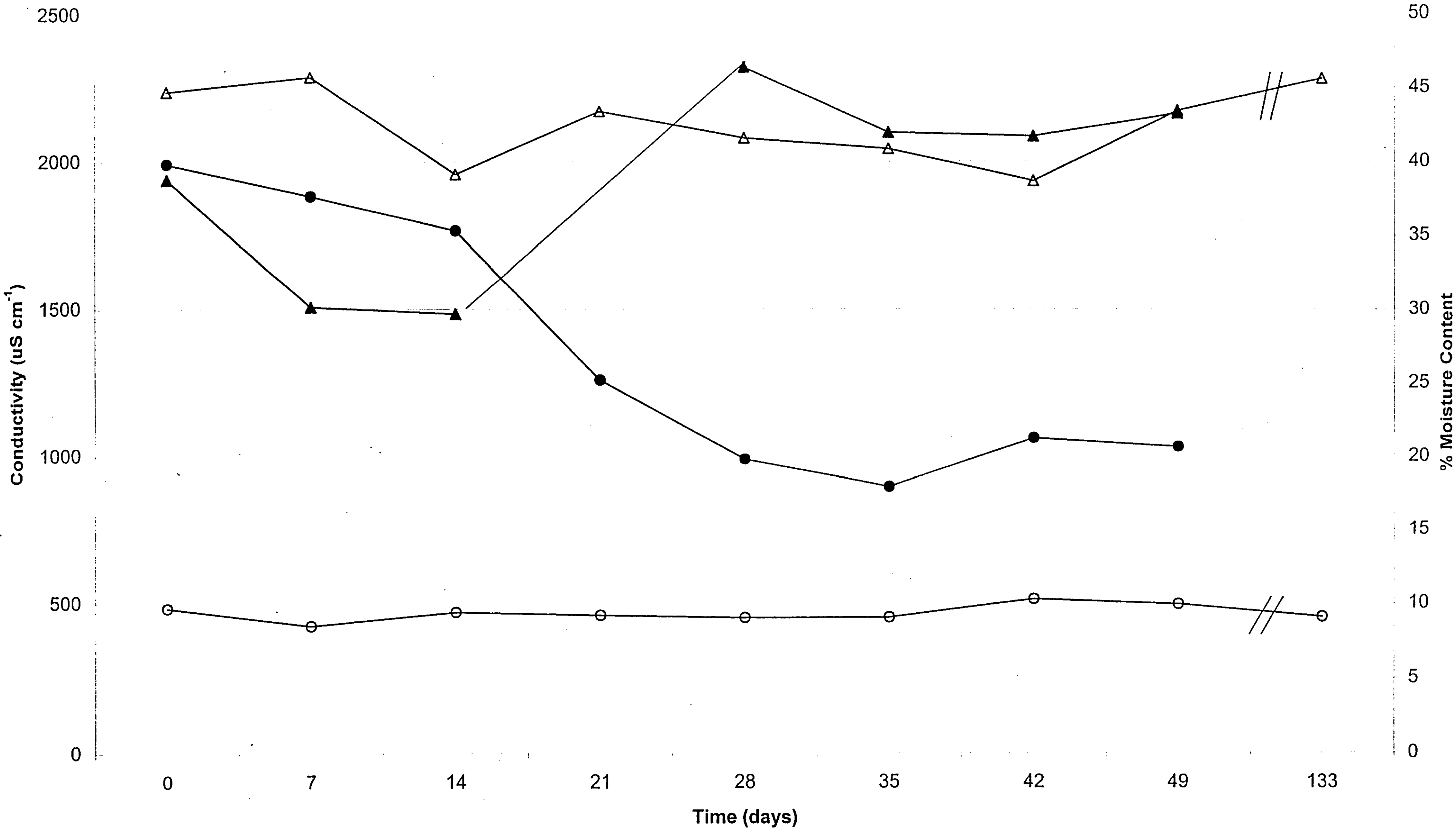
Figure 43: Riverside composting Field Trials 1 (winter) and 2 (summer). Mean conductivity values ($\mu S\ cm^{-1}$) and percentage moisture content (%) of windrow material from six subsurface (0.3m-0.5m deep) bilateral sampling points.

(○) Mean conductivity values Field Trial 1 (winter)

(●) Mean conductivity values Field Trial 2 (summer)

(△) Mean moisture content Field Trial 1 (winter)

(▲) Mean moisture content Field Trial 2 (summer)


2500
2000
1500
1000
500
0
Conductivity (uS cm-1)
50
45
40
35
30
25
20
15
10
5
0
% Moisture Content
0
7
14
21
28
35
42
49
133
Time (days)

change in moisture content in field trial 1 was reflected in the stability of the conductivity data, with any changes due to variations in the moisture levels. This observation was more strongly developed in field trial 2, with greater variation in moisture contents resulting in more diverse conductivity readings. The larger total rainfall during parts of this trial not only increased the moisture content of the material reducing the concentration of salts, but also appeared to cause a leaching of these soluble salts out of the material, thus markedly reducing the level of conductivity over time. The leaching of soluble salts is not uncommon at composting sites and many modern sites are constructed on concrete pads with in-built drainage and leachate collection systems. Such systems are employed to limit the environmental impact that leachates have on the surrounding water table (Rynk & Richard, 2001). Conductivity measurement is useful in the profiling of waste materials for composting, as it gives a gross estimation of the levels of soluble nutrient salts present. The results from this study showed that the poorer quality winter material (and less active windrow) had a low conductivity value. The better quality summer waste (and more active windrow) had a high initial conductivity reading, but it was subject to environmentally induced leaching over time. As excessive levels of such chemicals can be toxic to both microorganisms and plants, monitoring of feedstocks and eventual final product for extreme levels of conductivity is valuable. Earlier research (Irvine, 1999) indicated that the increased conductivity of initial feedstocks, due to exposure to seasonal road de-icing salt was carried through to the final product. Therefore, assessment of conductivity of feedstocks is valuable in limiting the inclusion of high salt content materials into the composting system. Materials of this nature could be pre-washed and / or mixed with low-salt items prior to windrow formation. Conductivity assessment as a process monitor is not advisable, as the data from these field trials showed no clear reflection of the state of the process, but rather the chemical nature of the material and its interaction with the climate (although increased solubility could be brought about by microbial action, and this may have contributed to the drop in conductivity seen in field trial 2). However, as a tool for checking the environmental impact of any runoff produced around a windrow it is important. The data suggest that feedstocks with a high soluble salt content could be subject to leaching and therefore, conductivity measurements of both the feedstocks and the surrounding soils and points of water collection on a composting site should be made on a regular basis.

THE COMPOSTING PROCESS AND HEAVY METAL CONCENTRATIONS

Heavy metals are found naturally in soil and water environments, and are typically at low concentration, apart from locations where geological formations exist that contain ore bearing rocks. Normally toxic to biological activity at high concentrations, some elements such as copper and zinc are essential micronutrients at low concentrations. Anthropogenic activities, particularly since the beginning of the industrial revolution in the late 17th century, have resulted in widespread contamination of the environment with a range of heavy metals. In recent years a combination of changing industrial activities, greater awareness and tougher environmental legalisation have started to reduce the impact of heavy metal pollution in the West. However, in many other parts of the world this is not the case and damage to the environment continues. Additionally, heavy metal contamination is cumulative and persistent in nature. Metal based pollutants, unlike organic chemical pollutants (e.g. complex hydrocarbons), are not broken down over time, but largely remain intact, only changing in speciation or availability and thus accumulate in the environment (Kamnev & van der Lelie, 2000).

Potential heavy metal pollution is typically directly related to the closeness to centres of human activity. Hence the soil, water and vegetation in and around towns and cities is on average more contaminated than rural locales. Therefore, the use of wastes derived from urban situations (such as sewage sludges and botanical debris from parks, gardens and roadsides) in composting operations has prompted concern about the potential of elevated levels of such pollutants in composts and by extension to food crops grown in such products (National Research Council, 1996; Sterrett *et al,* 1996).

However, there are problems related to the practical assessment of heavy metals in both feedstocks and composts. Heavy metals are a diverse range of chemical elements, which can exist in a range of different species or forms. These can have a range of differing binding, adsorption and absorption characteristics to various molecules and materials. Although general trends do exist, there is no one test for heavy metal contamination or one form of extraction procedure that is ideal for all metals in all situations (de Abreu *et al,* 1996). Classically total metal assessments were made. However, these are often of limited value when considering the environmental impact of metals, where availability to biological systems is more important than the theoretical total concentration within a given sample. Therefore, a range of different extraction procedures have been developed, where some are termed sequential and employ a variety of different extractants which fractionate the metals into those amounts which are bound to different molecules within the sample matrix. Other systems are based on determining the level of metals potentially available to plants. One such extractant is EDTA, which was employed in this study to investigate the concentrations of plant-available heavy metals within the composting system and represents a good general purpose extractant capable of profiling a range of common metals within a sample with relationship to plant availability (Ure, 1990; Rowell, 1994). This is important, as the ultimate use of composts is to support the growth of plants, including food crop examples where the level of metal potentially available for uptake is of concern. This should be linked to studies of actual plant uptake and storage to assess the level of impact.

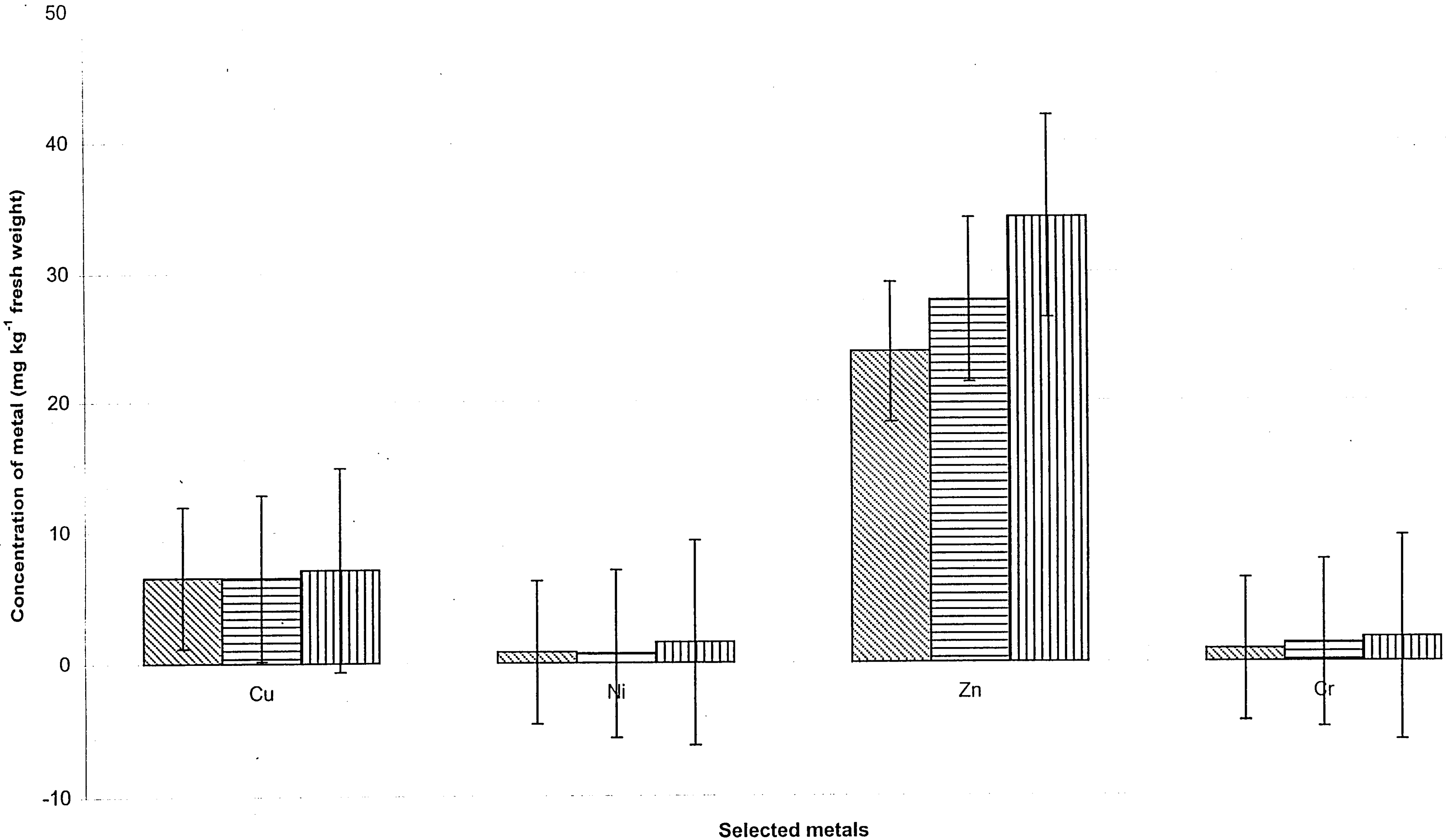
Two experiments are presented. Using samples collected for physical and chemical analysis from field trial 1 (Figure 44), EDTA extractable levels of copper (Cu), Nickel (Ni), Zinc (Zn), Chromium (Cr) and Cadmium (Cd) were assessed at windrow establishment (fresh material), during the main active composting phase (3 week old

Figure 44: Riverside composting Field Trial 1 (winter). Selected heavy metal concentrations (copper (Cu), nickel (Ni), zinc (Zn) and chromium (Cr)) (mg kg^{-1} fresh weight) in fresh, three week and 19 week old windrow material (sampled from six subsurface (0.3m-0.5m deep) bilateral sampling points) extracted using EDTA at pH7, indicating potentially plant available metals. Error bars represent the standard error of the data sets.

( ) Fresh material

( ) 3 week old material

( ) 19 week old material



Concentration of metal (mg kg^{-1} fresh weight)
50
40
30
20
10
0
-10
Cu
Ni
Zn
Cr
Selected metals

material) and after an extended windrowing period (19 week old material), to assess the concentrations of each of the metals and how these changed over an extended time period of open windrow composting. Metal concentrations were determined after EDTA based extraction *via* atomic absorption spectrophotometry (AAS) using the methodologies presented in the General Experimental Methods chapter. The results revealed the presence of detectable levels of EDTA extractable copper, nickel, zinc and chromium, but no cadmium was recorded. The highest heavy metal concentrations in the samples were for copper and zinc (both essential plant micro-nutrients). None of the recorded metal concentrations were high and could not be considered environmentally "unfriendly". In general terms this reveals that the feedstocks used in this composting operation were not heavily contaminated with easily available heavy metals. This is understandable as, although urban in nature, no industrially derived materials were used in the operation and Dundee is not a large city with intense traffic flow or major heavy industry to place an environmental burden upon it. Concentrations of the metals detected in the experiment rose throughout the period of the trial. This was due to a combination of microbial activity changing the chemical composition of the waste material that can result in an increase in the extractability of some metal species, and also a concentration effect due to the reduction in mass of the waste materials as decomposition occurs over time. Metals cannot be broken down or degraded like organic based materials, and therefore, an initially heavily contaminated feedstock will result in a compost with a high total metal content. However, the leachable fraction may well be reduced in a final stable compost because of the high pH and organic matter content both of which are known to keep metals in a bound state (Alloway, 1990; Gove *et al,* 2001). Thus, of the levels of metals recorded in trial 1, the amount which would be water extractable is even less than that which was estimated as being plant available. Plants and their associated microbes have biological mechanisms, which can alter the chemical composition of the soil around them to allow the uptake of metal ions, in the case of non-essential metals by mistake. This is the basis of the modern waste management technique called phytoremediation, whereby selected plant species (termed accumulators) have the ability to uptake and store from the soil or water highly elevated amounts of different metals without damage (Chaney *et al,* 1997; Garbisu & Alkorta, 2001).

The second experiment used weekly samples from trial 2 (Figure 45), and in addition to the five metals investigated before, lead (Pb) was also assessed. The experiment aimed to provide detail about the changes in EDTA extractable metals during the active phase of windrow based composting on a weekly basis. Detectable levels of all six metals were found in all weekly samples, with the concentrations of copper, zinc and lead being highest. Concentrations of chromium and cadmium were very low throughout the trial, although some variation in EDTA extractable levels was detected, with the concentrations of chromium decreasing during the trial, therefore, becoming less available to plants. Cadmium initially showed an increasing trend, indicating increased solubility before a downward trend was established. As the concentrations were low there was little to suggest any adverse environmental impact related to the cadmium and chromium content of the samples. Levels of nickel were similar to those recorded in trial 1 and showed little change throughout the monitored period, suggesting that the availability of this metal changed little during the composting process. The initial concentration in the second field trial of copper was approximately double that of the first. This suggests that the composition of the feedstocks in this trial contained higher levels of EDTA extractable copper, which may reflect contamination from copper containing pesticides or other chemical agents, or perhaps indicate that the copper contained within plant tissue is found mainly in the leaves and other green parts of the plant during the summer. This type of material is readily degradable, hence the high initial copper concentrations. The lack of this waste during the winter or the translocation and / or conversion to less available forms within woody parts may result in a reduced concentration of EDTA extractable copper in winter wastes.

Figure 45: Riverside composting Field Trial 2 (summer) Weekly mean heavy metal concentrations (copper (Cu), nickel (Ni), zinc (Zn), chromium (Cr), cadmium (Cd) and lead (Pb)) (mg kg^{-1} fresh weight) in windrow material (sampled from six subsurface (0.3m-0.5m deep) bilateral sampling points) extracted by EDTA at pH7 indicating potentially plant available metals. Error bars represent the standard error of the data sets.

( ) Fresh material

( ) I week old material

( ) 2 week old material

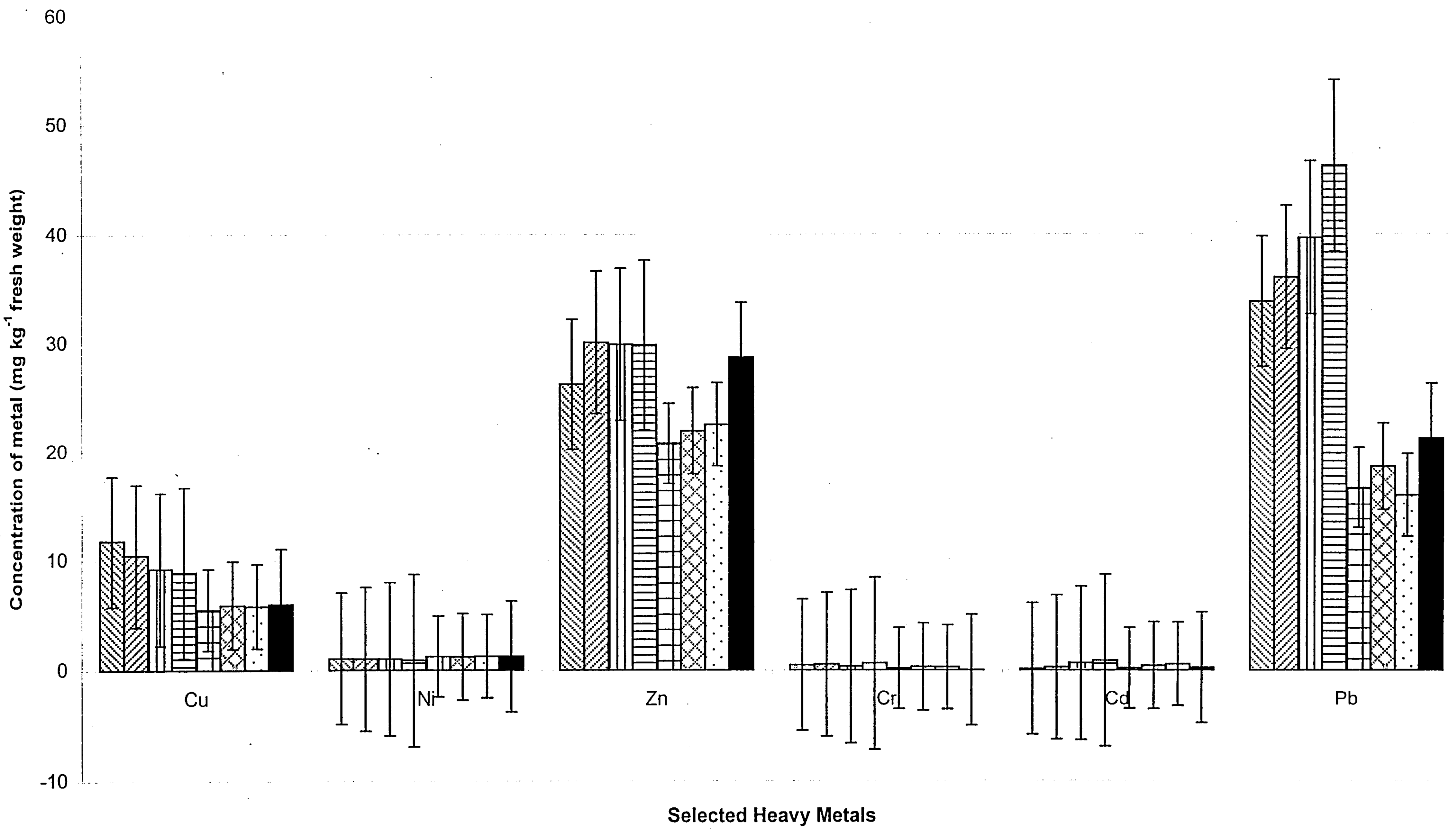
( ) 3 week old material

( ) 4 week old material

( ) 5 week old material

( ) 6 week old material

( ) 7 week old material



60
50
40
30
20
10
0
-10
Concentration of metal (mg kg^{-1} fresh weight)
Cu
Ni
Zn
Cr
Cd
Pb
Selected Heavy Metals

Copper concentrations displayed an initial downward trend during the first three weeks, before stabilizing at week 4. The results showed that copper became progressively less available during the most active phase of the composting process. This was probably linked to the increasing pH value observed during this time. High pH is well known to reduce the availability of most heavy metals. The analysis of the data showed a strong negative correlation coefficient (-0.793) between pH values and copper concentrations. Zinc concentrations varied, showing an initial increase before a stable period, then reduction and a later peak. Lead also displayed a pattern of increase during the first 3 weeks, before rapid decline and stabilization. It is suggested that during the period of the most intense microbial activity when temperatures were most elevated, that microbial activity increased the availability of both zinc and especially lead (additionally also perhaps copper) due to changes in the water-soluble organic carbon concentration (Hsu and Lo, 2001). As the compost matured and microbial activity declined (especially in the outer-most layers of the windrow), this increased availability decreased. The time frame of approximately 4 weeks is in accordance with the general downward trend observed in windrow temperatures (in particular the more peripheral regions) at this time.

The results from both heavy metal experiments showed that a range of EDTA extractable heavy metals was found in both summer and winter windrows, although concentrations were not considered to be of environmental concern. The levels of both copper and cadmium were slightly higher in summer time derived waste and may indicate seasonal variation in the availability of these metals. In the short term, i.e. during the most active phases of the composting process, the availability of some metals, notably zinc and lead, temporally increased. In the long term, due mainly to the reductive process of composting, heavy metals concentrations may appear to increase, however due to the combination of high pH and stable organic matter content of composts the movement of these metals is likely to be retarded.

CONCLUSIONS

The field trial experiments demonstrated clearly that temperature is the key, most dynamic and sensitive practical process parameter of open windrow urban green waste composting. Temperature measurement reflects well the level and duration of microbiological activity within a windrow, therefore providing the composter with an accurate indication of the "*state-of-play*" inside the windrow. This study provided a unique high resolution picture of temperature development, trend and distribution within large scale urban green waste derived windrows during the seasonal composting of both winter and summer feedstocks. Additionally, physical and chemical measurements were undertaken on a regular basis throughout both composting operations.

Simple overall mean windrow temperature plots are of limited value when assessing the extent of thermophilic (optimal degradation) temperatures, heat retention and the potential for pathogen reduction within a typical windrow. There is a lack of sensitivity to heterogeneity that results in an incomplete and potentially misleading image of temperature trends with the windrow. The data from these experiments have shown clearly that temperature levels and development are not uniform in either a temporal or spatial sense within a windrow. The outer layers of the structure do, at times, experience thermophilic temperatures. However, unlike the inner core regions they are largely unable to retain this heat. Sustained thermophilic temperatures mainly occur within the more insulated inner regions of a windrow. These areas are, therefore, where the highest rates of organic matter decomposition and pathogen kill take place. However, the data showed that even here there was often a high degree of temperature variation. This supports the need for turning of the windrow contents to maximize mixing and allow for optimum physical structure for better composting efficiency.

Winter weather conditions (e.g. low ambient temperatures) did not stop the sustained development of thermophilic conditions within the windrow or the general composting of waste materials. The feedstocks available during the winter months are characteristically of a poor quality (mainly woody in nature) and are more difficult to microbially digest. This tends to retard the composting process and results in a less efficient operation, with reduced periods and volume of windrow exhibiting thermophilic temperatures. The data showed that the range of temperatures found in both the winter and summer windrows were very similar, the major difference being the duration of thermophilic temperatures within each of the test windrows. The chemical and physical composition of feedstocks within the summer established windrow aided the rapid and prolonged development and distribution of thermophilic conditions for a greatly extended period of time without the advantage of turning. However, both field trial windrows exhibited noticeable downward trends in temperature after 3 to 4 weeks, suggesting conditions within the windrows were then less optimal (this time interval may represent the natural turning cycle of this type of windrow). These temperature effects were reflected in changes in the physical and chemical parameters of pH, bulk density and organic matter content for example.

The major environmental factor, which affected the development and retention of elevated temperature, was increased windspeed of, even short duration. This was most noticeable in the winter-established field trial, whereby large zones of the windrow in contact with the prevailing wind were prevented from developing and, importantly, retaining thermophilic temperatures. Only during periods of reduced windspeed was heat generation essentially possible. Although this cooling effect was most pronounced during the winter and was probably combined with the poorer physical and chemical qualities of the windrow to increase heat loss from the structure, this was also noted during the summer. Depths of up to 1 metre deep (dependent on height and overall cross-sectional width of the windrows) were mainly affected by the chilling effect of the increased wind, which is a significant portion of the volume of a typical windrow. The clear cooling effects resulting from a slightly increased windspeed (approximately 15MPH) were not beneficial in terms of decompositional efficiency or pathogen reduction effectiveness. There was no positive value gained (e.g. improved gas exchange by the elevated windspeed), as any gain was cancelled out by the greater levels of heat loss displayed in these zones. Areas unaffected by the wind supported sustained thermophilic temperatures indicating an active aerobic microbiological community.

The physical and chemical assessments undertaken indicated that some of these parameters could display valuable links to the composting process. Analyses like pH (increases over time), bulk density (increases over time) and organic matter (decreases over time) measurements reflected in part the composting process and changes within the windrow. However, none did so to the same degree as the temperature assessments. However, these parameters have value in the profiling of the waste material initially and the final compost product. Experimentation showed that the pH of the feedstock material did not fall initially because of the production of sugar-acids, but rose dramatically within the first 24 hours of composting. It is suggested that sugar-acid production is a mesophilic low temperature activity and upon windrow establishment and increased temperature it ceases. Moisture content and conductivity measurements were not sensitive at reflecting the composting process, and no clear links between observed temperature trends and the composting process could be found. Both parameters however, would have value during the characterization of both feedstocks and composts. Conductivity assessment of the environment surrounding a windrow is useful in the monitoring of potential leachate problems, especially from the more nutrient rich feedstocks gained during the summer months.

In general, EDTA extractable heavy metal concentrations were low. In the short-term (i.e. during the most active phase of the composting process), the availability of copper, zinc and lead varied, at times increasing. This was linked to changes in the chemical nature of the feedstocks due to microbial action. In the longer term, metal concentrations tended to stabilize, but appeared to increase over time due to a concentration effect caused by the reduction in volume of the waste materials resulting from the degrading of the feedstocks.

A combination of daily windrow temperature plots derived from readings from all regions of a windrow (both sides; "*bottom-middle-top*") of reasonable number points, cumulative temperature plots, frequency and distribution plots, as well as graphs of simple mean overall windrow temperature, are the primary tools that a compost site operator should undertake if a valid and practical temperature profile of windrow is to be used to maximize the efficiency and safety (pathogen kill) of the composting process.

The windrow temperature data presented in this study demonstrates that current temperature assessment methods practiced by commercial composters, (e.g. the six data point system advocated by the UK Composting Association; Composting Association, 2002) are flawed. The use of a limited number of temperature readings concentrating on the core regions of a windrow is likely to result in a biased and incomplete picture of temperature development within the structure. Therefore, the operational efficiency and safety of the composting process will be comprised. There is a demand for a novel method of temperature assessment for windrows.

The field trial studies have provided unique insights into the windrow based composting process. The detailed study of temperature development and distribution within typical green waste windrows, and factors affecting these, will facilitate in the development of a physical model of such a process. The field trial data will allow the design of a physical model based upon the characteristics observed in the field within large-scale windrows and not simply a generic composting process.

CHAPTER 4 – DEVELOPING A PHYSICAL MODEL OF OPEN WINDROW COMPOSTING

INTRODUCTION

Small-scale experimental systems have been employed by researchers since the beginning of the scientific study of composting. For example Waksman *et al* (1939), studied the influence of temperature on the microbial population within stable manure composts using earthenware pots and Carlyle and Norman (1941), undertook a series of experiments investigating microbial thermogenesis during the decomposition of plant material by use of flask based systems. However, it was not until the mid-1950s that modern model composting systems were developed (Wiley, 1956 & 1958; Schulze, 1962). At this time there was, particularly in the USA, a growing interest in the composting of MSW (Haug, 1993). This was in response to a need to modernize the waste management industry and develop more responsible methods of waste treatment (compared to uncontrolled dumping and burning for example). Composting was seen as a means of safely ("*hygienically*") treating and stabilizing the expanding volume of MSW being produced, as well as making an agriculturally useful agent. In-vessel composting systems were strongly promoted at this time by the waste management industry as means of safely, quickly and efficiently treating waste flows and the physical composting models developed at this time reflect this. Models were designed in an attempt to optimize the conditions and engineering designs of the full-scale composting plants, which were being advanced at this time.

Since the early 1970s, further reports have been published upon the development of physical composting models (Jeris and Regan, 1973a, b & c; Suler and Finstein, 1977; Ashbolt and Line, 1982; Sikora *et al*, 1983; Bach *et al*, 1984; Nakasaki *et al*, 1985; Hogan *et al*, 1989; Adenuga *et al*, 1992; Palmisano *et al*, 1993; Tseng *et al*, 1995; Gilmour *et al*, 1996; Stombaugh & Nokes, 1996; Kaiser, 1996; Papadimitriou & Balis, 1996; Baker *et al*, 1999; Bari *et al*, 2000a & b; Huang *et al*, 2000; Kim *et al*, 2000; Bari & Koenig, 2001).

These models have largely either attempted to model a generic composting process or have been used as a test-bed for the development or optimization of in-vessel composting systems. Increasing numbers of models are emphasizing the importance of the microbiological aspects of the composting process over the chemical, physical and engineering considerations. This is clearly vital if realistic models of composting are to be developed (Hogan *et al*, 1989; Tseng *et al*, 1995; Papadimitriou & Balis, 1996).

The value of physical compost models is clear; they can allow novel insights to be made into what is a complex microbiological process. They can facilitate the optimization of process and feedstock management parameters as well as identifying the shortcomings in existing methodologies. Their small-scale means only limited volumes of waste materials and space are required and often an accelerated result can be achieved. The controlled conditions allow for the ease of detailed monitoring and safety for the operator. The use of models in a predictive manner to ascertain whether a particular set of conditions, feedstock mix (including contaminated examples) will compost in an effective way is also a valuable use of a good physical model. It can additionally be noted that all the above features have strong economic benefits which are important to the modern waste management industry.

As stated, previous models have been based upon in-vessel designs, which perhaps from an engineering point of view lend themselves better to the task than other systems. However, in addition to the use of fermenter-style arrangements, researchers have often employed a range of unnatural features in their designs, including external heating (often to induce the exothermic characteristics of composting) and insulating jackets. Additionally, within those models, purporting to represent the general composting reaction, little association to field conditions have been made. These factors may limit the value of such models.

Interestingly, commercial composting operations are dominated, not by in-vessel systems, but by open windrow procedures. Windrowing is economic, essentially simple to operate, robust and versatile, thereby making it an ideal choice for the waste management industry. However, composting by the use of open windrows, is often perceived as being a natural and / or uncontrolled process, therefore perhaps limiting the need or practicality of a physical model. Windrow based composting is in some ways both the former, but the lack of detailed knowledge of internal windrow processes, enhances the requirement for a realistic physical model of windrow composting. This would reduce the "uncontrolled" aspects of the process (art *vs.* science) and allow composters to further develop this valuable waste management technique.

Experimental Rationale

The aim of this part of the project was to develop and test a novel physical compost model specifically of open windrow composting, based in part on the findings of the two field trials representing typical winter and summer composting of urban green waste within windrows. The development and distribution of elevated temperatures within the experimental composting mass was an important concern. The model was designed to reflect the unique features found in such systems and use them to advantage and thus produce a realistic and practical physical model of windrow based composting.

METHODS

DESIGN AND CONSTRUCTION OF PHYSICAL MODEL

Although in the field a windrow comprised of the green waste to be composted is not contained, it was clear that in a laboratory situation some form of containment would be required. However, it was important to prevent such a system from developing simply into a small-scale in-vessel composter. Any design had to have a large enough feedstock capacity to allow for a representative volume to be contained and to encourage self-heating and slow heat loss (insulation provision). An acceptance that there may be the need for a low level of artificial *internal* heating to counter the difficulty of heat loss from a small volume of waste material was made. Provision for an aeration system had to be made because any form of containment would reduce natural airflow from the exterior and encourage an anaerobic state. The model had to have a temperature monitoring system. Figure 46a presents a schematic diagram of a theoretical design for a physical composting model showing the principle features of such a system for studying open windrow composting.

Figure 46b shows a schematic representation of the experimental physical compost model. The letters in the following text refer to those found in the key for Figure 46b. The model comprised a redundant upright freezer unit (A) (safely stripped of coolants and electrically isolated). This gave a large thermally isolated space (1.4m high x 0.59m wide x 0.50m deep) with ease of access. Fitted into this space was the main composting chamber (B). A wooden (19mm x 38mm white wood, "Focus Do It All", Arbroath, UK) rectangular framework with legs was constructed (operational dimensions; 0.88m high x 0.53m wide x 0.47m deep) and each side panel (excepting the front, top and bottom) was covered with plastic greenhouse shading mesh (D) (Homebase, Dundee, UK). Metal aviary mesh (E) (Handy Panels 13mm x 13mm mesh size, Sentinel Pet Products, Sheffield, UK) was then hung on the side panels to provide additional strength. A removable front panel was constructed from the wire mesh to allow for the filling and emptying of the model. Using rectangular steel framing (Black steel tube 25mm x 25mm, RS Components Ltd., Corby, Northants, UK) and plastic coated steel meshing, a legged base unit (I) was constructed and slotted within the wooden frame (0.25m high). Attached to the wire meshed covered side panels *via* plastic cable ties was a system of repeating coiled plastic tubing (termed cooling coils) (C) (Standard Polyurethane Tubing ID 6mm, RS Components Ltd., Corby, Northants, UK). This was linked *via* an access port on the front door of the freezer to a circulating water bath (O) (LKB Bromma 2209 Multitemp, LKB Produckter AB, Bromma, Sweden). Importantly, there was a space (J) between the cooling coils and the walls of the former freezer compartment. A series of bamboo garden canes (F) were positioned and tied

Figure 46a: A schematic diagram of a theoretical design for a physical model of open windrow composting. The principle features of the system have been highlighted. Diagram not to scale. The following key describes the main features identified on the schematic diagram.

A- Environmental chamber (to provide controlled conditions)

B- Open framework container for feedstocks (model windrow)

C- External ambient temperature simulation system

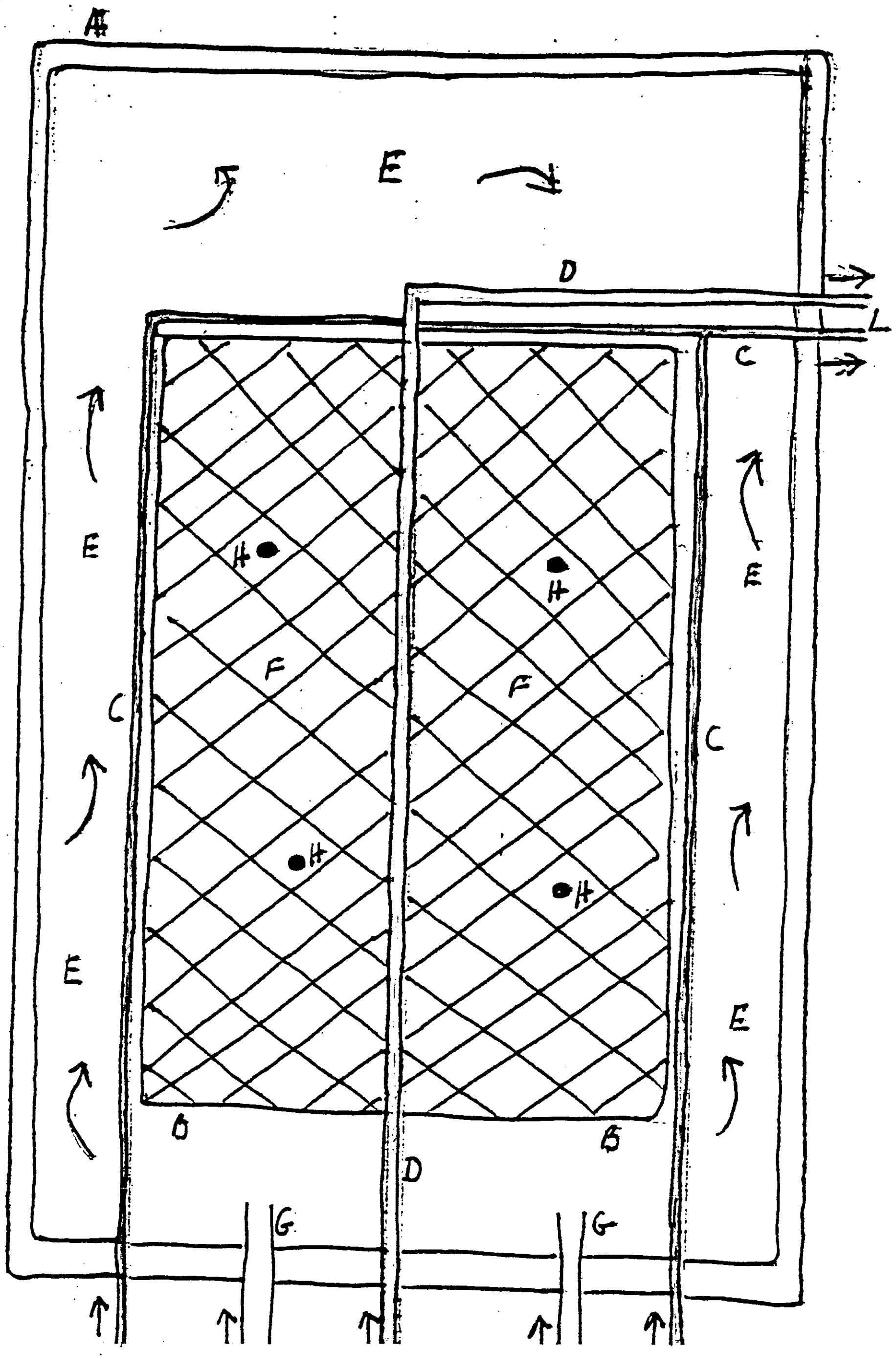
D- Internal feedstock background heating system (to stimulate natural microbial activity)

E- Air space (for the free movement of air, moisture and heat)

F- Compost feedstocks (shredded urban green waste)

G- Aeration system (to maintain an aerobic state)

H- Temperature monitoring system (thermocouples)



A
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G

Figure 46b: Schematic diagram of the major features of the novel physical compost model designed to reflect open windrow composting presented in this study. Based on a former upright freezer, with cage-like composting chamber, with heating, cooling, aeration and temperature monitoring mechanisms. Door removed for clarity. Diagram not to scale. The following key describes the main features identified on the schematic diagram.

A- Ex-freezer cabinet walls

B- Wooden Framework, comprising the main composting chamber (model windrow)

C- Cooling coils (water filled plastic tubing)

D- Inner plastic mesh (attached to wooden framework)

E- Outer metal mesh (attached to wooden framework, cooling coils hung here)

F- Bamboo cane supports for heating coil (H) and thermocouples (G)

G- Type K Thermocouples (selection only shown)

H- Heating coils (water filled plastic hosing)

I- Metal base unit (supports loaded composting chamber above)

J- Free airspace

K- Leachate collection tray

L- Air lines

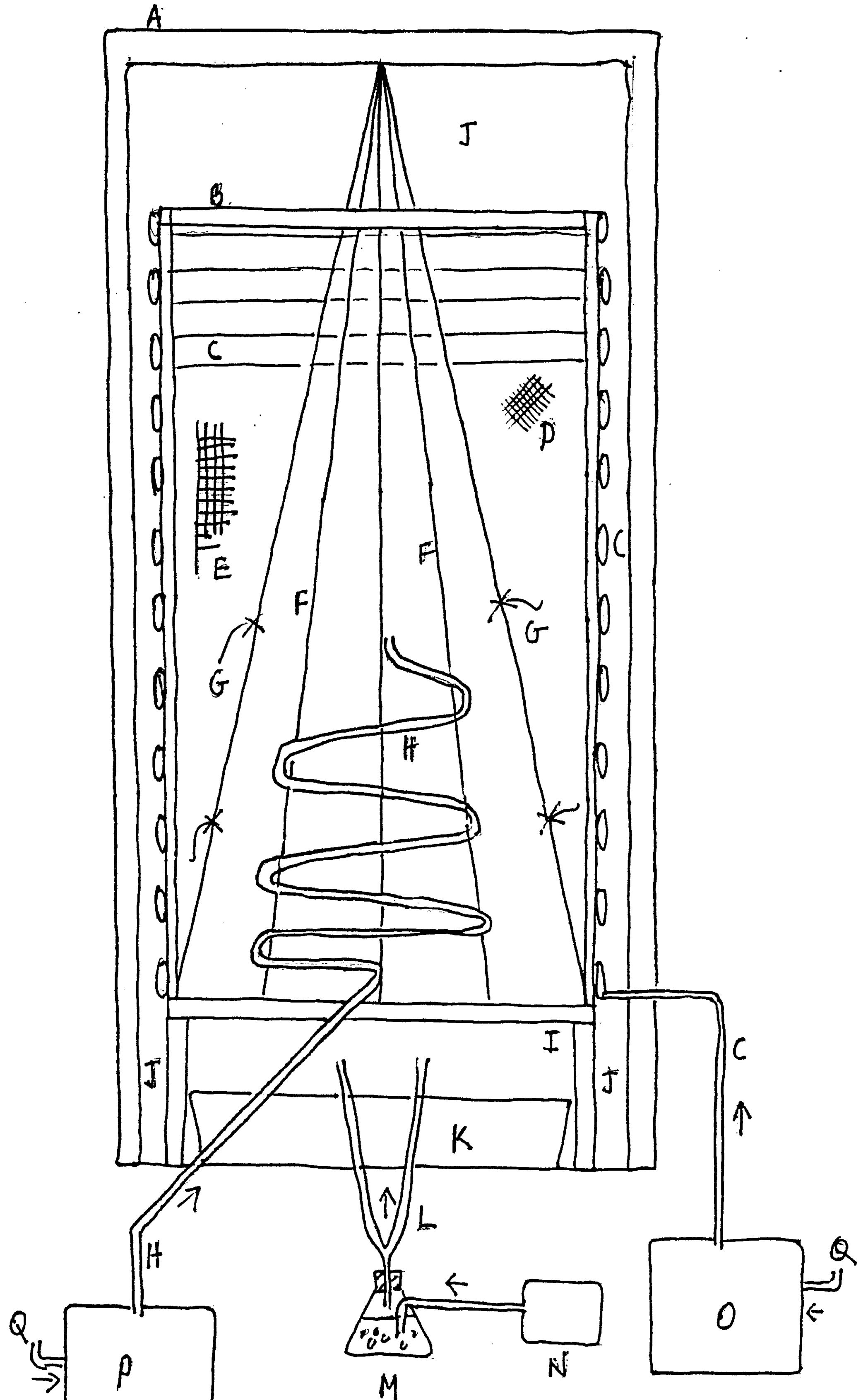
M- Buchner flask air moistener

N- Air pump

O- Water heater-circulator 1 (cooling coils)

P- Water heater-circulator 2 (heating coils)

Q- Return flows



A
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Q

in a wigwam arrangement inside the wooden framework and a plastic hose (H) (Standard Clear Reinforced PVC hose, ID 10mm, RS Components Ltd., Corby, Northants, UK) was attached *via* plastic cable ties in a coiled manner (termed heating coils). This was linked *via* a door-based portal to water heater-circulator unit (P) (Tecam Circulator C400, Technical Equipment Ltd., Duxford, Cambs, UK). In the space under the composting chamber a large plastic photographic developing chemicals style tray (K) was located as a leachate collection system. Aeration was supplied by the way of an aquarium type air pump (N) (Elite 802, Rolf C Hagen (UK) Ltd., Castleford, W. Yorkshire, UK) with an output of 5 l min^{-1} passed through a water trap (M) consisting of a Buchner flask, to pre-moisten the air in order to reduce drying effects. Two airlines (L) entered the unit at the base just above the leachate tray. In addition to the aforementioned freezer door located ports, holes were drilled at the top for air-vents to allow for freer movement of air and heat and where required for thermocouples for temperature measurement. Internally, 8 thermocouples (G) (type K, 2m long PVC coated individually numbered; Kalestead Ltd., Braintree, Essex, UK) were positioned with cable ties on vertical bamboo canes within the feedstock container or directly to the wall of the model in the following arrangement; middle (core) (0.3m below surface), right hand upper front, left hand upper front, (each side, 0.4m high from base, 0.12m deep from front, 0.12m in from side) right hand lower back, left hand lower back, (each side, 0.3m high from base, 0.3m deep from front, 0.12m in from side) compost surface, internal roof and floor of ex-freezer unit. Additionally, two thermocouples were positioned in the laboratory, one adjacent to the model equipment (room temp 1) and one approximately 2m away (room temp 2) to record background external temperature trends.

FEEDSTOCKS FOR MODEL

Seasonally available green waste material was diverted from Dundee City Council's Discovery Compost programme, and shredded at the Environmental and Consumer

Protection Department's composting site at Wright Avenue, Riverside, Dundee, using a TIM SD2000 shredder (Tim Maskinfabrik A/S Fabriksvej 13, Denmark). The botanical material was derived from civic amenity sites, compostainer collections and commercial gardening contractor's waste. The feedstocks were bagged and transported to the laboratory and loaded into the experimental model within 2 hours of collection. During this time samples were removed for physical and chemical assessments. Feedstocks were loaded manually into the composting chamber. This minimized the problem of over compaction and clumping of the materials, and ensured good porosity and mixing of the composting mass.

MODEL OPERATION AND TEMPERATURE MONITORING

Once the composting chamber was filled with feedstocks, the external door was closed and secured, and the two water circulators (heating and cooling) were switched on. Normal operating parameters were an output temperature of 5°C or 15°C (approximately the external ambient temperature) for the cooling coil, and an output temperature setting of 65°C for the heating coil arrangement. Moist aeration was supplied to the unit at a rate of 5 $l\ min^{-1}$. All parameters were delivered in a constant manner over the period of an experimental run.

Temperature assessment was made immediately after the start of an experimental run. This was achieved by the use of a handheld thermocouple datalogging thermometer (Digitron 2088T, SIFAM Ltd., Torquay, Devon, UK), before downloading into a PC *via* a Digitron infrared Digilink unit. The data were captured and stored using Digitron V1.09 software, which enabled export to Microsoft Excel 97 (Microsoft Corporation, Redmond, USA) for further analysis. Additional temperature measurements were made on a regular basis throughout the length of a trial run, these varied between experiments.

PHYSICAL AND CHEMICAL ASSESSMENTS OF FEEDSTOCKS

Samples of shredded feedstocks were collected before entry into the compost model, and were subjected to select physical and chemical analysis using the methodologies presented in Chapter 2 (General Experimental Methods). These included, pH, conductivity ($\mu S\ cm^{-1}$), % moisture content, % organic matter content and bulk density ($g\ l^{-1}$).

RESULTS AND DISCUSSION

ESTABLISHMENT OF THE NON-BIOLOGICAL HEATING CHARACTERISTICS OF THE COMPOSTING MODEL.

A series of two experiments were conducted to establish the non-biological heating characteristics of the physical composting model. Figure 47 shows the results of the first experiment, when the model was run empty (i.e. no materials in the composting chamber). The following conditions were applied; the outflow temperature of the heating coil was set at 65°C and the cooling coil outflow temperature was set at 5°C, aeration was given at a rate of 5 $l\ min^{-1}$. The trial was carried out to establish the natural heating characteristics and distribution of temperature within the system caused by the heating, cooling and aeration mechanisms. The data presented in the figure demonstrate that there was a distribution of temperature according to position within the model. The lower regions exhibited the lowest temperatures, and exhibited a cooling effect. The greater the elevation within the model, the higher the temperature. This reflects the convectional movement of heat within the system (i.e. *hot air rises*). Importantly, after the initial rapid increase (or decrease in the case of the lowest regions) within 5 hours a steady state had been achieved, (i.e. no further changes in temperature occurred during the trial), until the heating, cooling and aeration systems were switched off (at 23.5 hours). After the heating, cooling and aeration mechanisms were switched off, the spatial distribution of temperature was lost and temperatures of all probes approximated 25°C to 26°C, before dropping back to around 22.5°C. A starting temperature of 22°C resulted in a peak temperature of 29°C and a low of

Figure 47: Physical compost model non-biological heating (empty) trial. Changes in temperature (°C) with Time (h). Model operational parameters set as, heating coil 65°C, cooling 5°C and air 5 l min^{-1} – switched off at 23.5h. Heavy horizontal lines indicate, 45°C (thermophilic region) and 55°C (pathogen kill temperature). Inset figure is given to enable analysis of fine detail. Full figure is given for direct comparison with data in Figure 48.

(○) Internal roof

(△) Top layer right

(□) Top layer left

(●) Middle layer left

(▲) Middle layer right

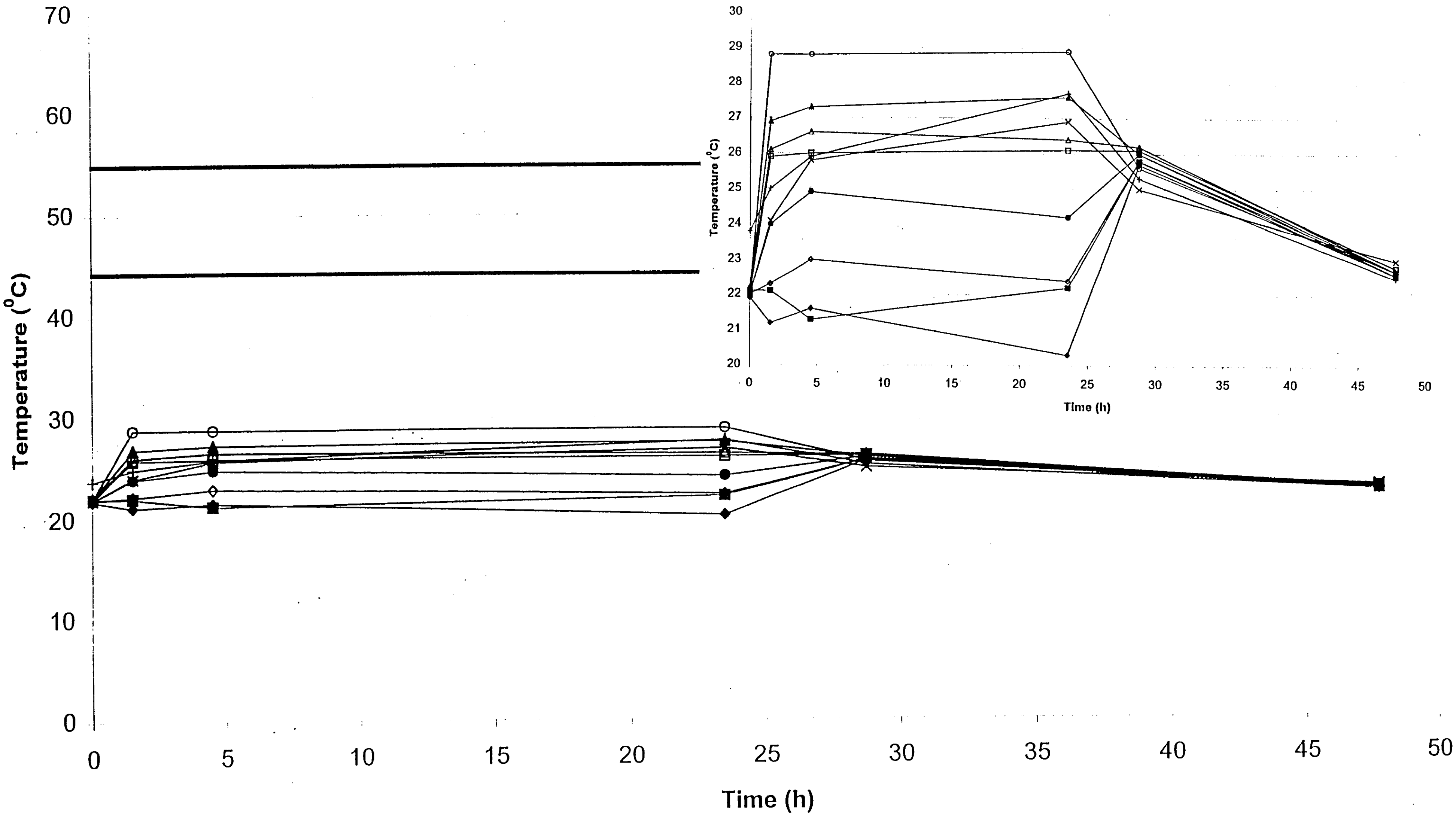
(■) Bottom layer left

(◇) Bottom layer right

(◆) Internal floor

(×) External room temperature 1

(+) External room temperature 2



Temperature (^{0}C)
70
60
50
40
30
20
10
0
0
5
10
15
20
25
30
35
40
45
50
Time (h)
Temperature (^{0}C)
30
29
28
27
26
25
24
23
22
21
20
Time (h)

20°C, giving a range of approximately 9°C within the interior of the container. The results of this experiment indicate that, under typical operating conditions, there was a controlled increase in temperature within the model over time (a maximum rise of approximately 7°C was observed), but that a steady state condition was quickly established. The distribution of temperatures within the model was related to its height, reflecting the upward movement of warm air inside the chamber.

The second experiment (Figure 48) was designed to investigate the heating and temperature distribution characteristics of the model system when charged with non-biologically active material. Sterile compost feedstocks would have been the ideal material; however, there was no practical method of rendering shredded green waste microbially sterile without affecting the physical and chemical characteristics of the material. Autoclaving would have significantly reduced the number of microorganisms, but not resulted in a sterile medium (Stenbro-Olsen, 1998), additionally it would have affected both the physical and chemical characteristics of the waste, thereby further limiting its suitability. Therefore, an alternative material was used, this being pre-packed straw used for pet bedding (Compressed Snooze, Marlow Farm Products, Clerland, UK) as sold from the local petshop. This material was clean, dry and free from contaminants such as glass and metal etc. The material used represented a pre-shred botanical material, not dissimilar to urban green waste. Importantly, due to its high content of microbiologically intractable carbon, low water content and poor nutrient balance, little active microbial decomposition was expected to occur during the period of the experiment. System parameters used in this experiment were, heating coil outflow temperature of 65°C, cooling coil outflow temperature set at 15°C and an aeration rate of 5 l min^{-1}. The results of the experiment are shown in Figure 48. A rapid rise in temperature was observed in a similar manner to that seen in Figure 47. Within a period of 24 hours an essentially steady state condition was achieved and continued until the end of the trial. Most temperature readings existed in a narrow, closely grouped band in the region of 35°C to 40°C and represent thermocouples

Figure 48: Physical compost model biologically inert feedstock (straw) trial. Changes in temperature (°C) with Time (h). Model operational parameters set as, heating coil 65°C, cooling 15°C and air 5 l min^{-1}. Heavy horizontal lines indicate, 45°C (thermophilic region) and 55°C (pathogen kill temperature). Inset figure is given to enable analysis of fine detail. Full figure is given for direct comparison with data in Figure 47. Diagram indicates positions of the thermocouples within the model.

(○) Surface (1)

(△) Right hand upper front (2)

(□) Left hand upper front (3)

(●) Middle (4)

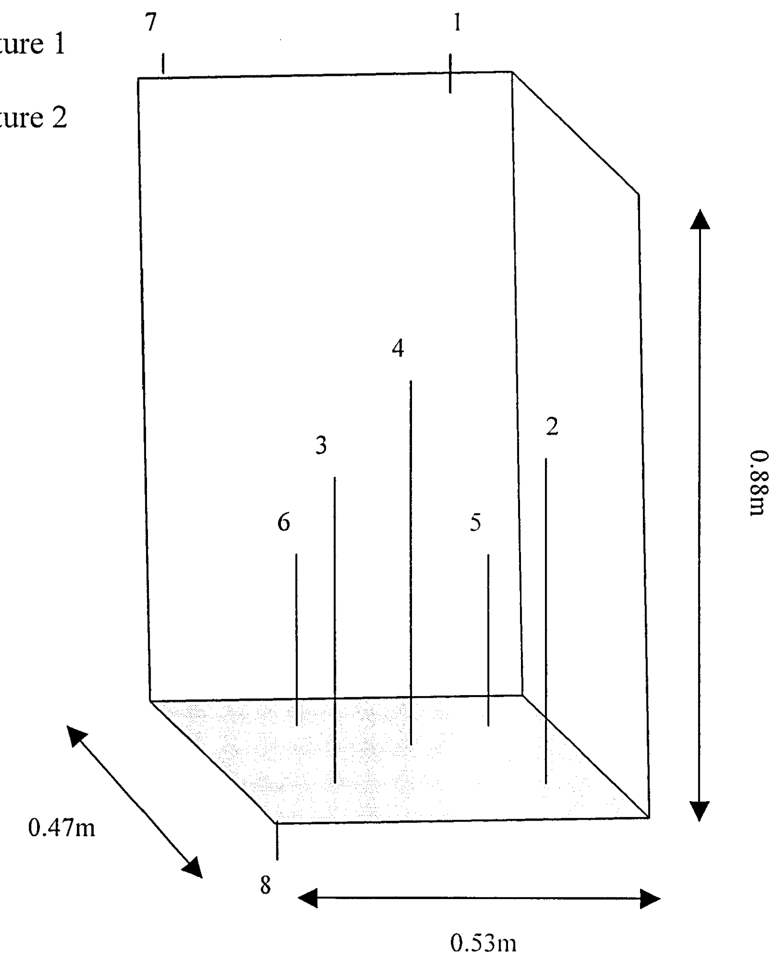
(■) Left hand lower back (6)

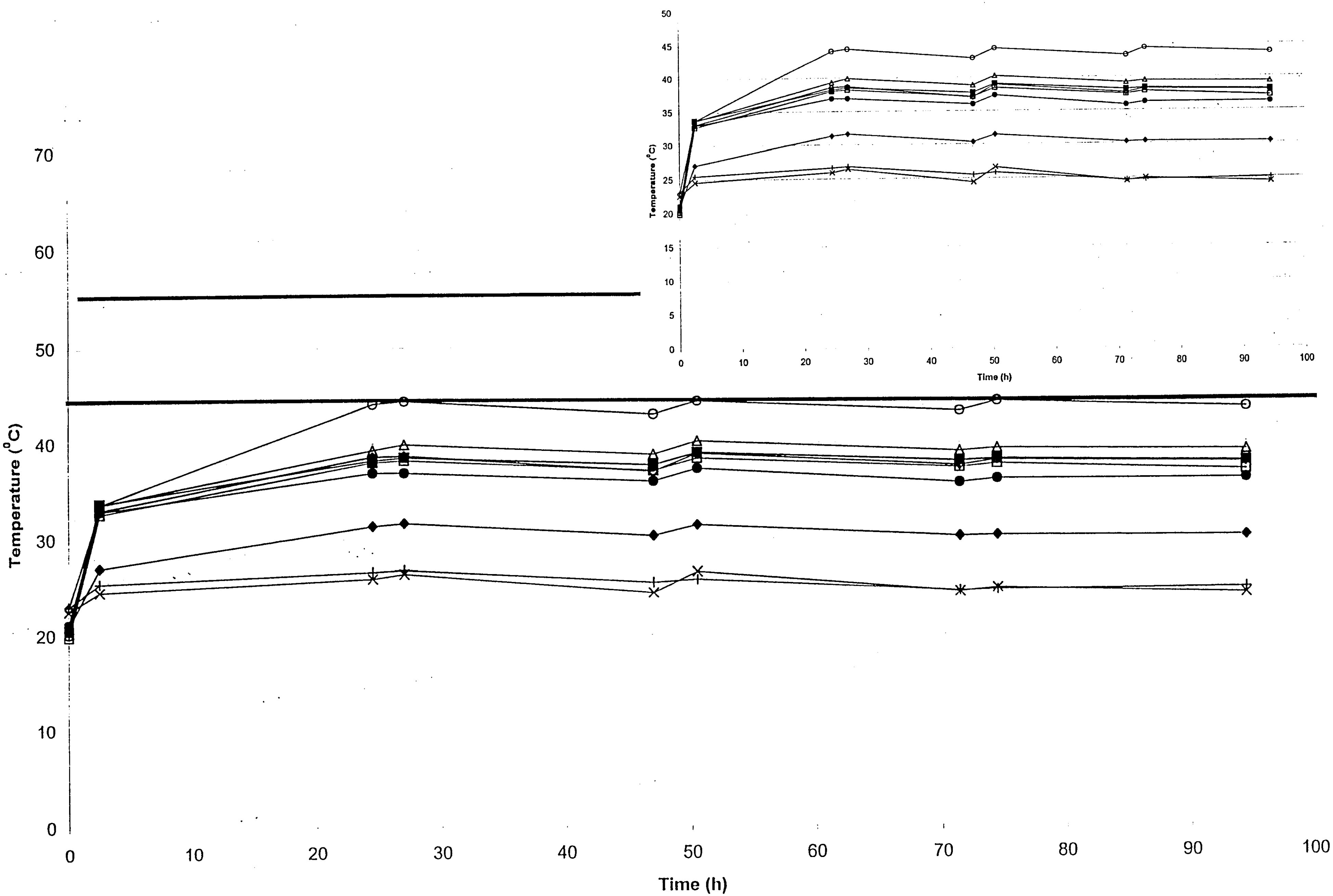
(◇) Internal roof (7)

(◆) Internal floor (8)

(×) External room temperature 1

(+) External room temperature 2





Temperature (^oC)
Time (h)

positioned within the feedstock material, (i.e. inside the composting chamber). The thermocouple located on the surface of the straw recorded a slightly higher temperature trend in the low 40°C range, but a steady state condition was otherwise observed. The region beneath the composting chamber (the internal floor) recorded the lowest temperatures in a similar manner to the first experiment. External room temperatures were steady and unrelated to the temperatures exhibited within the straw filled composting chamber. The results demonstrated that a rise of approximately 15°C to 20°C could be observed within the composting chamber when filled with (for the purposes of this study) a microbially inactive botanical material and operated under the above conditions of heating, cooling and aeration. This reflects that fact that heat can be trapped within the bulk of the material, unlike the conditions of the previous experiment, which showed temperature variations in a free airspace. This demonstrated the "blanket effect" of windrow-like situations. This of course better models the situation within a windrow environment. The temperatures experienced within the chamber were clearly not in the thermophilic region. This shows that the heating coil (outflow temperature of 65°C) did not overheat the material with the chamber. A steady state was quickly established and was prolonged throughout the length of the experiment. This suggests that once the model has heated-up and obtained the temperature distribution characteristics *via* the physical (non biological) actions of the heating, cooling and aeration mechanisms, then no further changes occur, (i.e. no independent heating or cooling behaviour is observed).

These two experiments provided valuable information on the natural physical heating and temperature distribution patterns observed within the compost model. This enabled comparison to be made between data derived from these experiments and those carried out using microbiologically active green waste.

COMPOSTING TRIALS USING GREEN WASTE FEEDSTOCKS

A series of trials was undertaken using freshly shredded green waste materials of a similar nature and origin to those used in the field trial experiments. Figures 49, 50 and 51 show the results of such experimentation, displaying temperature trends over time for three trials. Figure 49 represents spring waste, run under the conditions of; heating coil 65°C, cooling coil 5°C and aeration 5 l min^{-1} and Figures 50 and 51 representing early autumn waste, run under the following parameters; heating coil 65°C, cooling 15°C and aeration of 5 l min^{-1}. All three plots showed a similar pattern, which was quite distinct from that observed during the non-biological tests. A rapid rise in temperature, followed by a plateau, then a long steady decline in temperature was recorded. This is similar to the temperature trends exhibited in full-scale compost windrows. All three trials resulted in greater temperature elevation than that recorded for both the non-biological test runs. This indicates that an additional source of heat was available (the microbes), although it is also possible that the physical characteristics of the real waste were not exactly the same as the earlier straw and therefore, could have retained greater amounts of heat. There was no evidence of development of a steady state (i.e. a non-changing abiotic system, given that the physical conditions supplied to the model did not change over the trial), but instead the opposite, there was temperature variation and eventual heat loss. The development of thermophilic temperatures and a non-steady state, with temperature movements, was strongly suggestive of biological activity, (i.e. microbial growth and metabolism). The data therefore, indicate that the physical model encouraged and supported the growth and metabolism of microorganisms in a manner typical of a generic composting-type reaction.

The temperature profiles show that heat generation and distribution were not even throughout the composting chamber (i.e. the model windrow). The results reveal that middle regions, which were closest to the heating coil (and most insulated from the effects of the cooling coils), were not always the first to heat up or exhibited the highest

Figure 49: Physical compost model green waste feedstocks Trial 1 (spring derived waste). Changes in temperature (°C) with Time (h). Model operational parameters set as, heating coil 65°C, cooling 5°C and air 5 l min^{-1}. Internal and external air temperatures (°C) shown. Diagram indicates positions of the thermocouples within the model.

(○) Surface (1)

(△) Right hand upper front (2)

(□) Left hand upper front (3)

(●) Middle (4)

(▲) Right hand lower back (5)

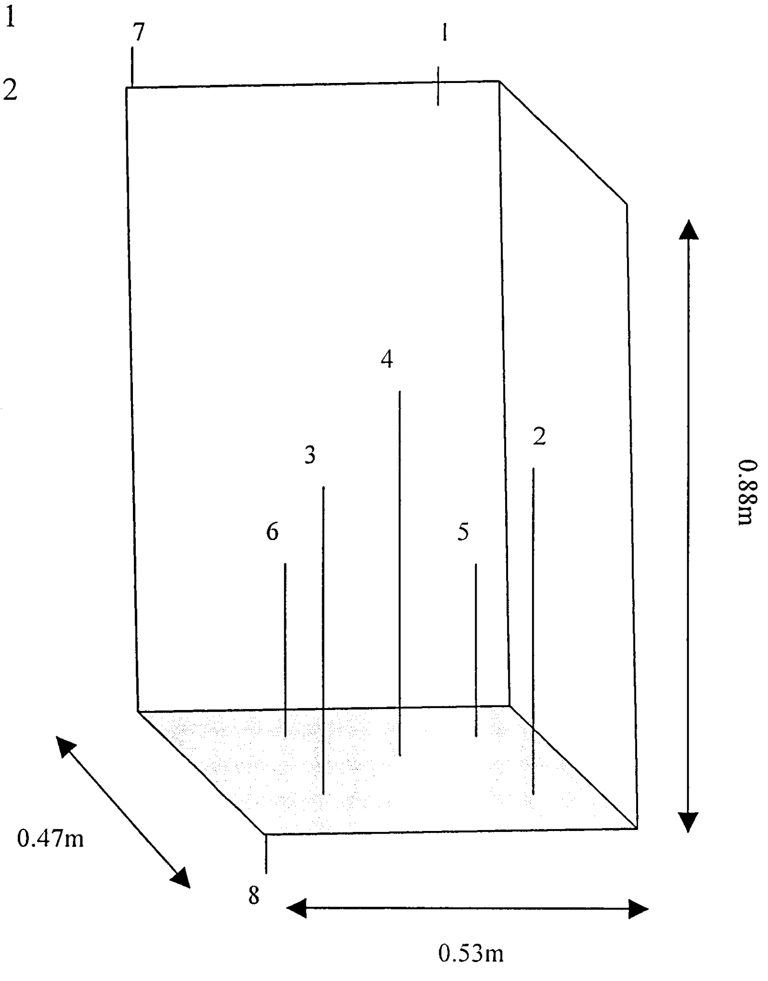
(■) Left hand lower back (6)

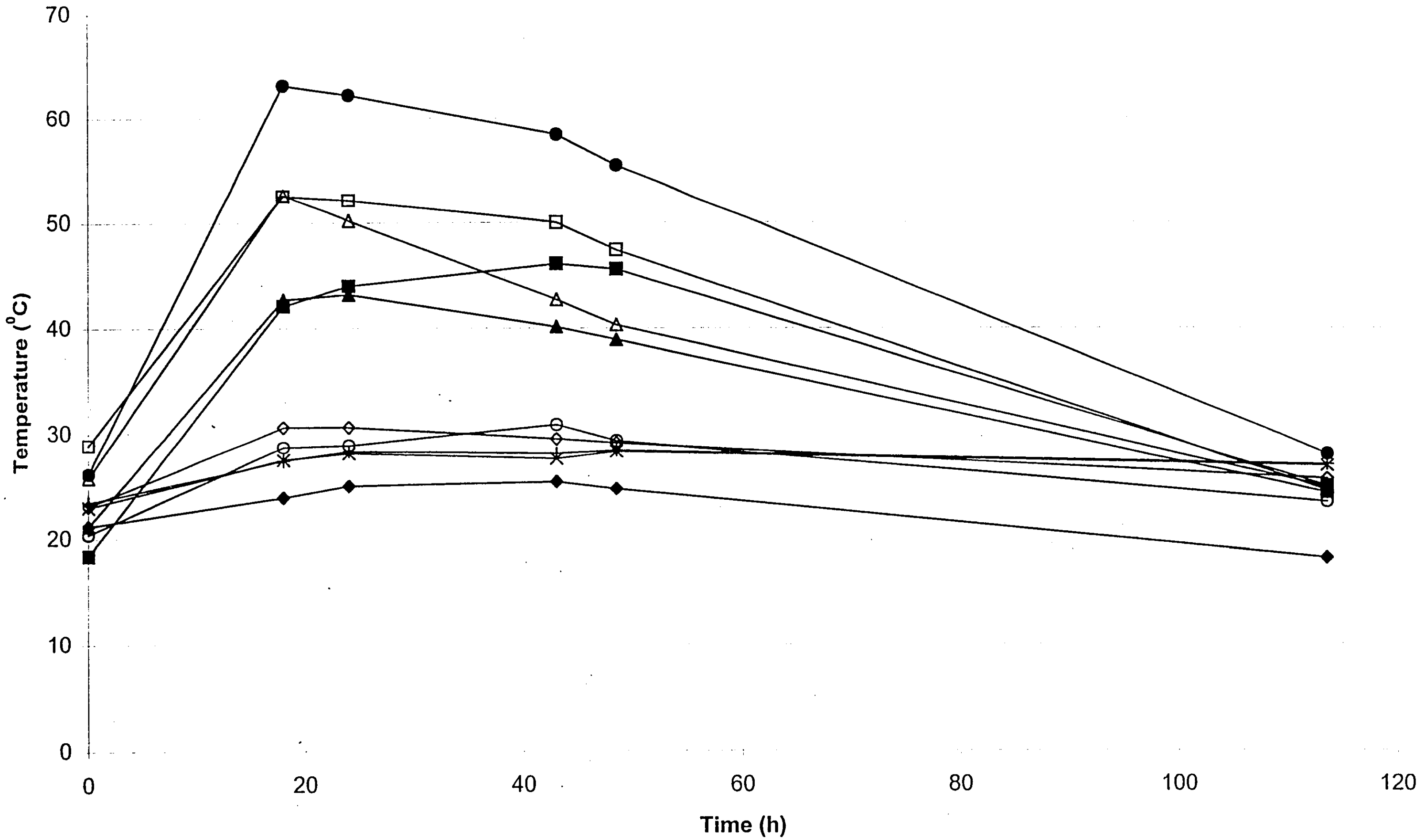
(◇) Internal roof (7)

(◆) Internal floor (8)

(×) External room temperature 1

(+) External room temperature 2





70
60
50
40
30
20
10
0
Temperature (°C)
0
20
40
60
80
100
120
Time (h)

Figure 50: Physical compost model green waste feedstocks Trial 2 (autumn derived waste). Changes in temperature (°C) with Time (h). Model operational parameters set as, heating coil 65°C, cooling 15°C and air 5 l min^{-1}. Internal and external air temperatures (°C) shown. Diagram indicates positions of the thermocouples within the model.

(○) Surface (1)

(△) Right hand upper front (2)

(□) Left hand upper front (3)

(●) Middle (4)

(▲) Right hand lower back (5)

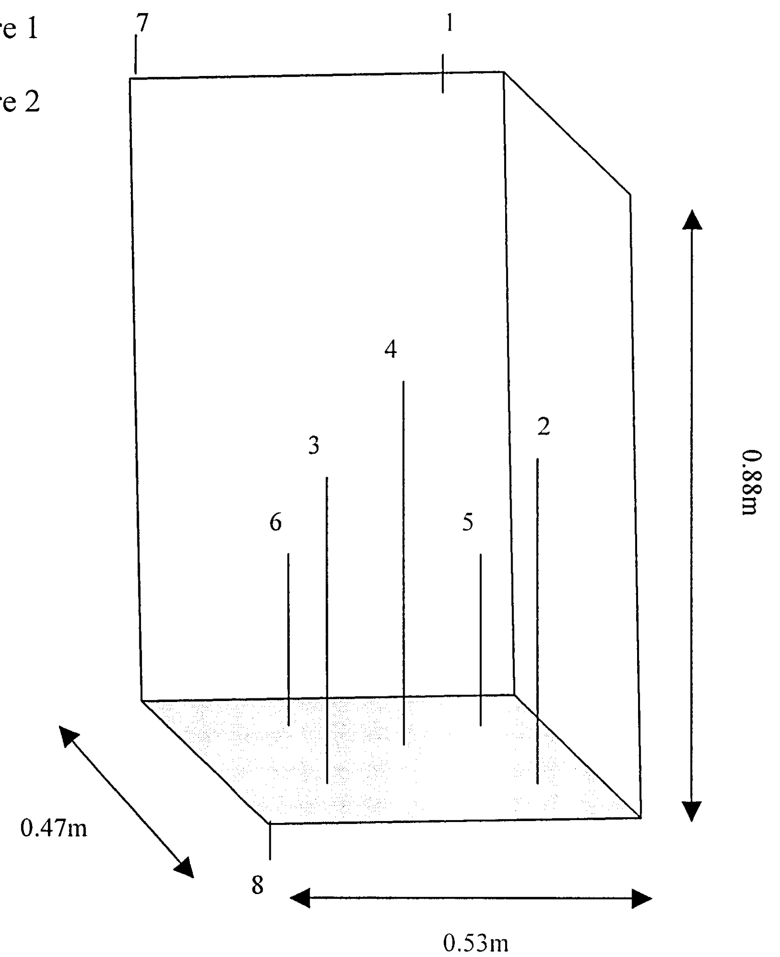
(■) Left hand lower back (6)

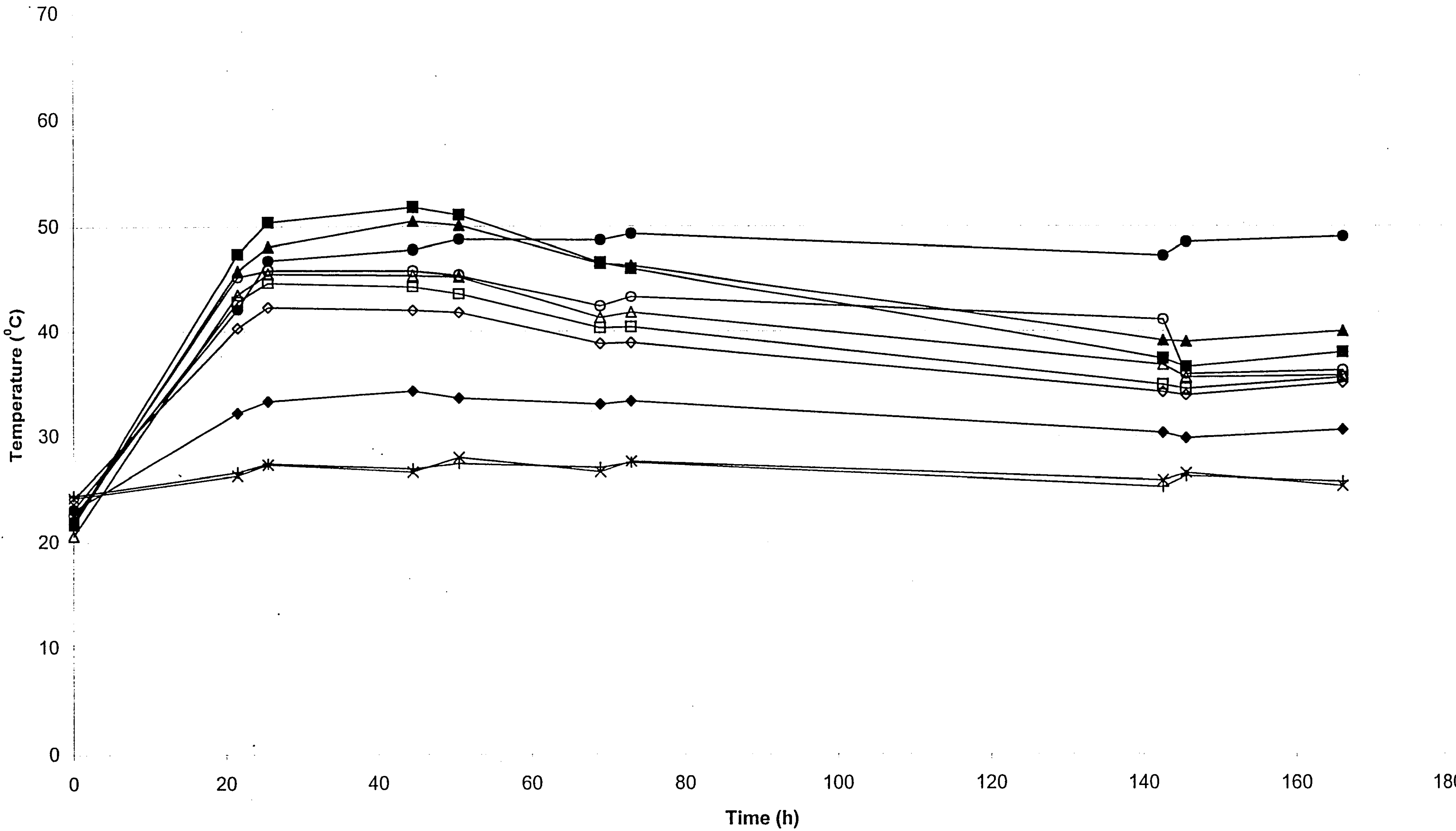
(◇) Internal roof (7)

(◆) Internal floor (8)

(×) External room temperature 1

(+) External room temperature 2





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Temperature (°C)
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Time (h)

Figure 51: Physical compost model green waste feedstocks Trial 3 (autumn derived waste). Changes in temperature (°C) with Time (h). Model operational parameters set as, heating coil 65°C, cooling 15°C and air 5 l min^{-1}. Internal and external air temperatures (°C) shown. Diagram indicates positions of the thermocouples within the model.

(○) Surface (1)

(△) Right hand upper front (2)

(□) Left hand upper front (3)

(●) Middle (4)

(▲) Right hand lower back (5)

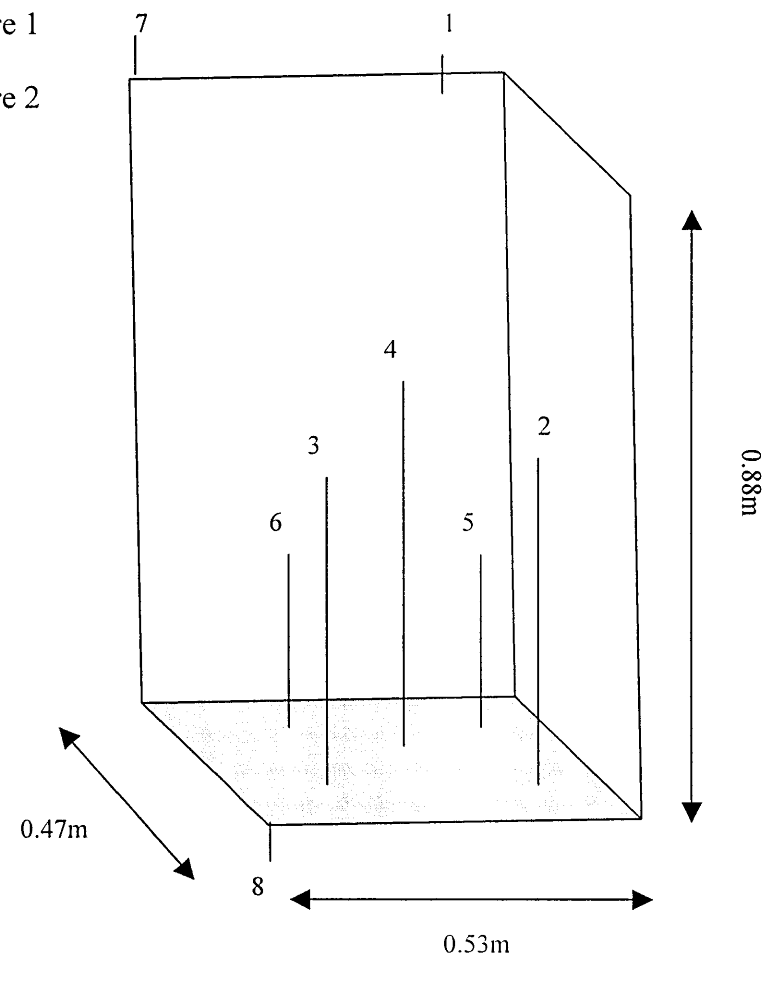
(■) Left hand lower back (6)

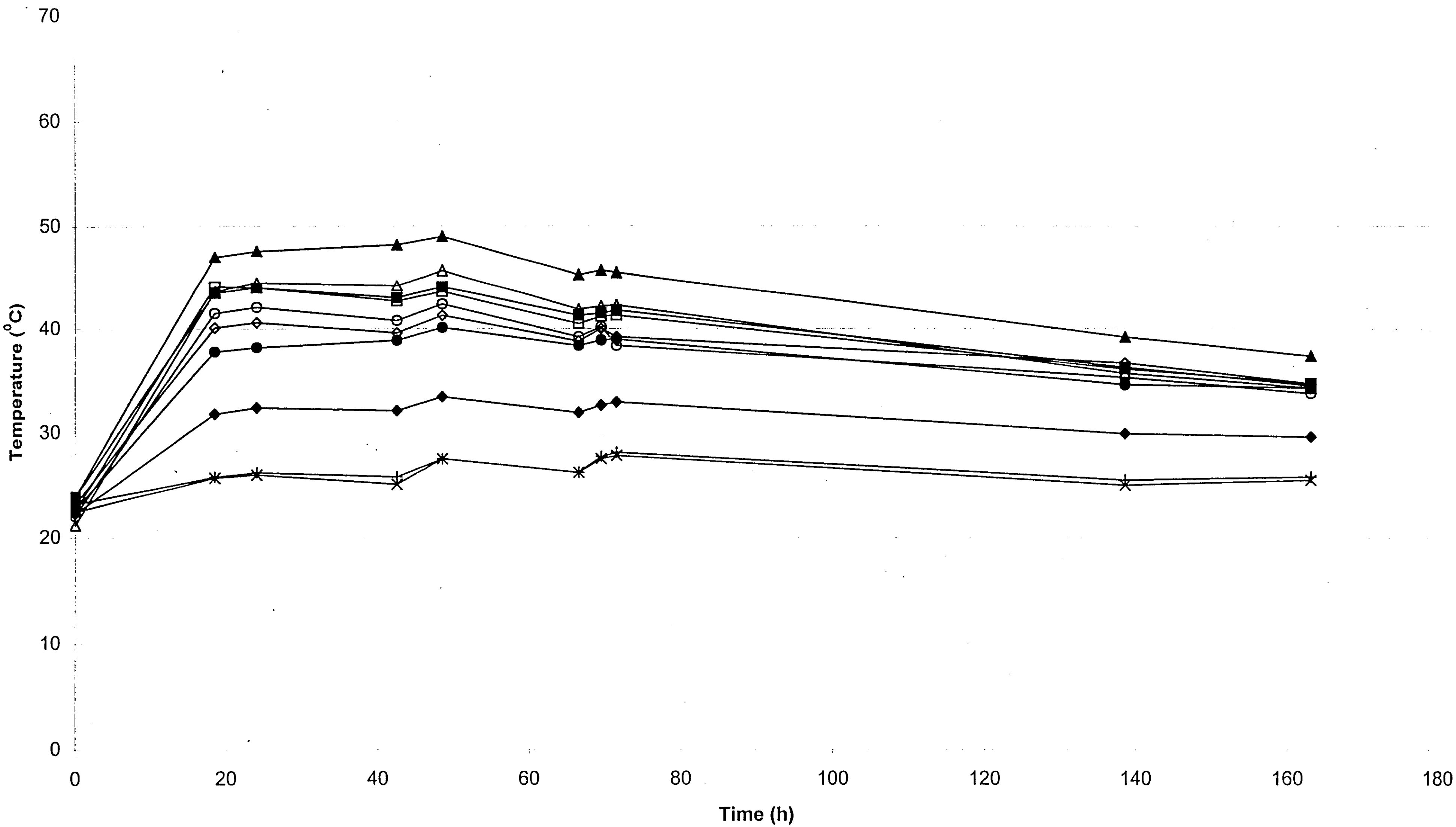
(◇) Internal roof (7)

(◆) Internal floor (8)

(×) External room temperature 1

(+) External room temperature 2





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Temperature (°C)
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temperatures. This is similar to the observed behaviour in the field trial windrows (Figures 9 to 13), whereby initial temperature development within the structures was started at one end of the structure. Additionally, data show that the development of elevated temperatures was not directly linked to proximity of the heating coils. The spread of temperatures (approximately 30°C within the data shown in Figure 49) was also reflective of that seen in the field trials (Figures 16 to 22), (i.e. there were non-isothermal conditions within the composting mass). This is indicative of the concept of various different niches existing within the feedstocks that support the growth and development of potentially differing microorganisms at varying growth rates.

The temperature profiles developed by the model were imitative of the primary stages of the composting process assessed within the field trial experiments, being the development of elevated temperatures by the indigenous and largely mesophilic microbial population within the first 24 to 48 hours after establishment, before the succession to a largely thermophilic community. The initial increase in temperature within the composting mass is typically following by a period, sometimes very short in duration and only clearly seen in the less insulated regions of a windrow, of depressed temperatures caused by the thermal inactivation of most of the mesophilic microorganisms.

Microbial activity as measured by temperature trends within model system was strongly reflective of this type of windrow based behaviour and reflects data collected during the field based composting of similar green waste materials (Chapter 3). The reduction in temperatures within the model system was clearly related to this thermal inactivation and succession loss of heat generation. The subsequent lack of recovery, even in the middle region is probably due to the small volume and therefore, large surface area of the waste material used.

This can be coupled to the environmental pressure caused by the cooling coils, which were designed to simulate the external temperature of a field windrow. It is important, when considering the design of the physical model, that in reality a windrow is not contained within a box, but is open to the environment and the climatological effects of that situation. Therefore, the insulated box of the former freezer unit making up the physical model was not there essentially to restrict the loss of heat from the feedstocks, but to allow the partial creation of a controllable micro-environment *via* the cooling coils, aeration and surrounding airspace within the outer shell of the model. This is different from the traditional design of numerous composting models where an external layer of insulation has been employed to limit heat loss and encourage thermophilic conditions within the feedstocks. Such an approach may be valid when modelling an in-vessel situation, but is clearly not so when simulating an open windrow composting system. In fact the data suggests that thermophilic temperatures can be obtained by microbial means without the need for direct insulation.

Figure 49 shows that when the cooling coil outflow temperature were set at 5°C, thermocouples placed outwith the feedstocks remained between 20°C to 30°C in a largely steady state. Limited variation did occur, reflecting the varying heat output from the composting mass on the surrounding air temperature, as a windrow would do to the air about them, (e.g. water vapour venting along the ridge). The temperatures within the feedstocks, however, were either in the thermophilic zone or on the border of it, approximately between 40°C and 65°C. In the period after the temperature plateau the decline was probably accentuated by the pressures of the cooling coils, which is inline with the phenomenon observed within the field trials when increased windspeed reduced the temperature of parts of the experimental windrows, and in the case of the southern sectors of the winter windrow clearly restricted the development of post succession thermophilic conditions. Therefore, experimental data from the physical model indicates that feedstocks were behaving in a fashion typical of a field sized open-windrow situation. A similar pattern of events is described in the trials shown in Figures 50 & 51 when the cooling coil temperature was set at 15°C. The background temperatures, (i.e. those outwith the feedstocks) were naturally higher than in the previous example, but were still lower than those within the feedstocks. The less harsh environmental conditions inside the model in these trials (akin to summer conditions) were reflected in part in the less dramatic downward trend in temperatures in these trials. Such effects were exhibited by the summer-established field trial, when more favourable external conditions seemed to prolong the elevation of temperatures within parts of the windrow. This demonstrates that an arrangement of cooling coils and aeration can be used to effectively simulate different environmental conditions inside a physical model of windrow based composting. Figure 52 shows a comparison of the mean windrow temperatures from Field Trial 1 (winter) and Field Trial 2 (summer) with the combined mean temperatures from the second and third green waste trials using the physical composting model, along with the respective air temperature, over the period of 24 to 166 hours. It can be noted that the mean temperature values for the summer and winter field trial windrows were quite different, although the temperature trend (shape) was similar. This suggests that seasonal variation in the feedstock composition and environmental pressures (windspeed) resulted in distinctive mean temperature profiles for each of the experimental windrows. The physical model temperature data are positioned between the two extremes of the full-scale windrows. The trend was closer in resemblance to the summer field trial data than the winter one and reflective of the seasonal nature of the waste material (early autumn) and the environmental conditions created within the model system. It can be seen that the mean temperature of the summer windrow and the combined mean temperature of the model at 24 hours were nearly identical and were thermophilic (no data were available for zero time temperatures for the field trials). The temperature continued to increase within the field-scale windrow for the next 48 hours before a plateau was reached. Such behaviour was likely due to the large volume of material present in the windrow and the resultant reduction in heat loss capacity. Temperature trends within the model showed that a steady state existed between 24 and 48 hours before a decline in mean temperature occurred.

Figure 52: Comparison of Field Trial 1 (winter) and 2 (summer) mean windrow temperatures (°C) with physical compost model combined mean temperature (°C) of green waste trials 2 and 3 (autumn derived waste) over the time period 24 to 166h, with respective air temperatures (°C) shown.

(○) Field Trial 1 (winter) mean windrow temperature

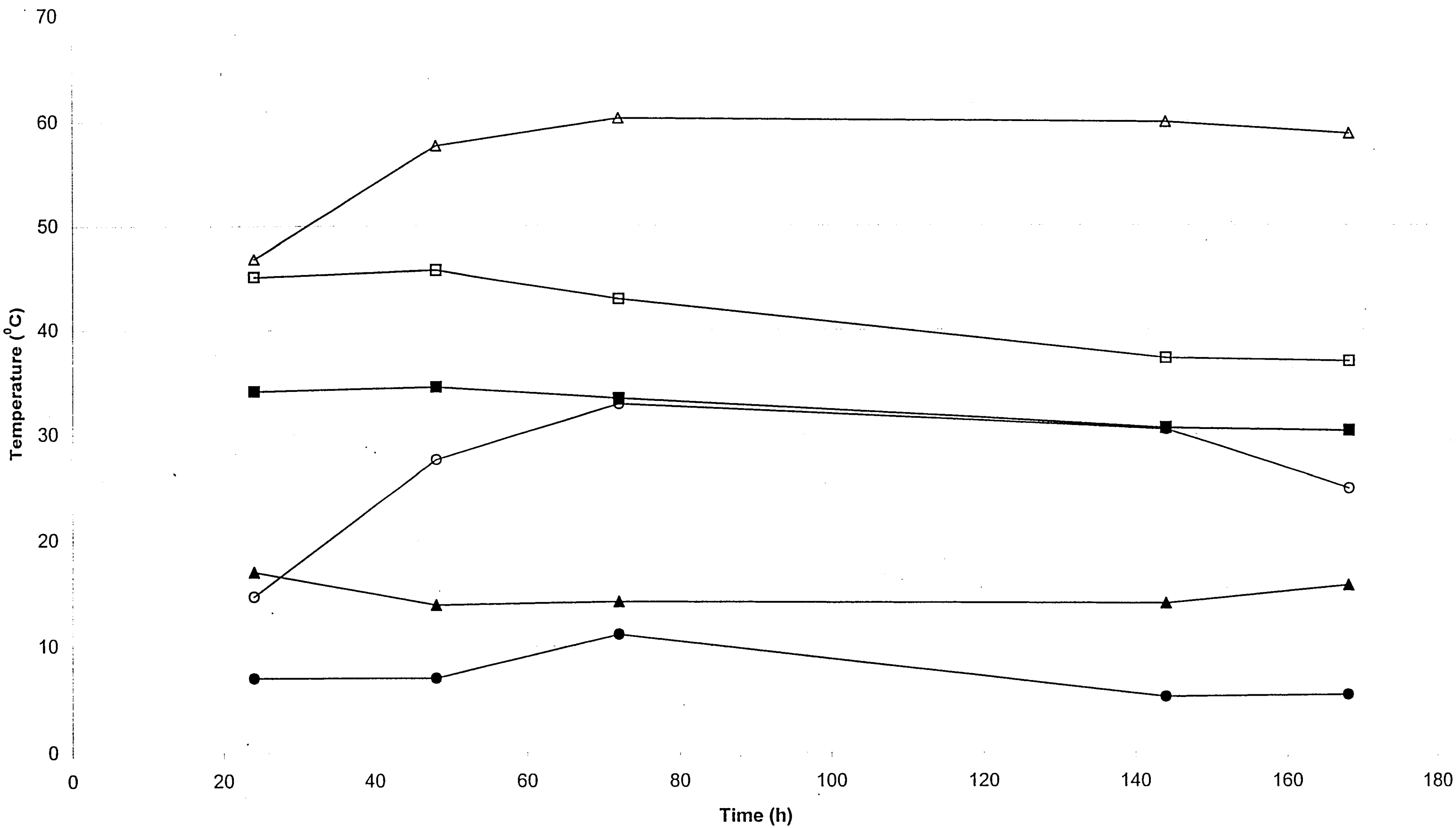
(▲) Field Trial 2 (summer) mean windrow temperature

(□) Physical model combined mean windrow temperature

(●) Field Trial 1 (winter) air temperature

(▲) Field Trial 2 (summer) air temperature

(■) Physical model combined mean air temperature



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Temperature (^{0}C)
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180
Time (h)

This is reflective of the greater heat loss capacity of the small volume of feedstocks contained within the model. The data illustrate that mean temperature patterns within the physical model reflected the general trends observed within field-scale windrows utilizing urban green waste feedstocks of similar seasonal origin (summer *vs.* early autumn).

Figures 53, 54 & 55 show cumulative temperature profiles for the straw feedstock trial and the second and third green waste feedstock trials respectively. It can be noted that both the straw (microbially inert) and the green waste feedstock trial's level of cumulative temperature within the first 24 hours were similar. This similarity during the initial 24 hour period suggests that much of the heat produced within this time was due to non-biological activity, (i.e. a combination of the effects of the heating coils and the insulating properties of the waste material within the model), or alternatively, that the rate of microbial heat production equaled that of heat loss within the system. It was only after 24 hours that a clear difference between the microbially inert and microbially active cumulative temperature trends developed, with the microbially active trials showing a greater level of cumulative temperature (101 to 123°C) than the inactive one (95 to 107°C). This trend continued, with the difference being more pronounced at 72 hours (140 to 169°C *vs.* 129 to 150°C). The data indicate that increased microbial metabolism and hence, thermophilic temperatures only occurred after 24 hours. There appeared to be a lag phase after establishment of the model before conditions were suitable for the rapid growth of microorganisms. This is not unexpected in such a system. The main function of the heating coils was not to heat the waste up to and maintain thermophilic conditions, but rather to help "*kick-start*" the process and provide background heating. This would be comparable to the pre-establishment heat present in pre-compostable material at the very beginning of the windrow process, coupled with the insulation effect of this material. The relatively small volume of waste material meant that excessive heat loss and difficulty in establishment of thermophilic activity were clearly problematic.

Figure 53: Physical compost model biologically inert feedstocks (straw) trial. Cumulative temperature (°C) over time (h). Model operational parameters set at, heating coil 65°C, cooling coil 15°C and air 5 l min^{-1}. Diagram indicates positions of the thermocouples within the model.

(○) Surface (1)

(△) Right hand upper front (2)

(□) Left hand upper front (3)

(●) Middle (4)

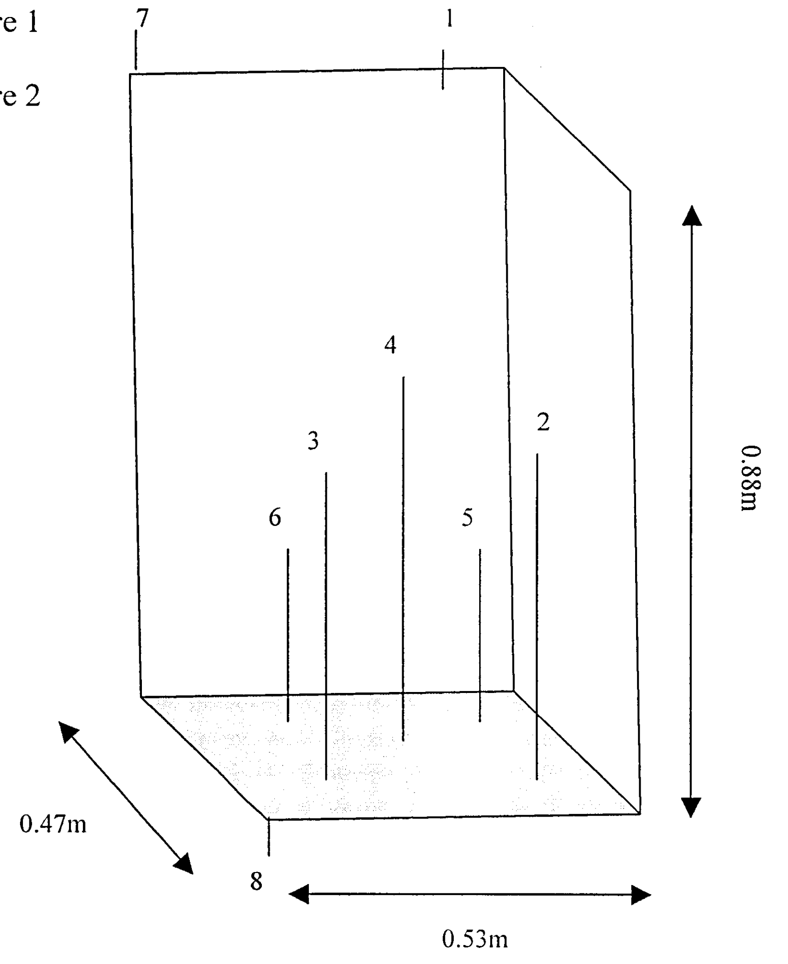
(▲) Left hand lower back (6)

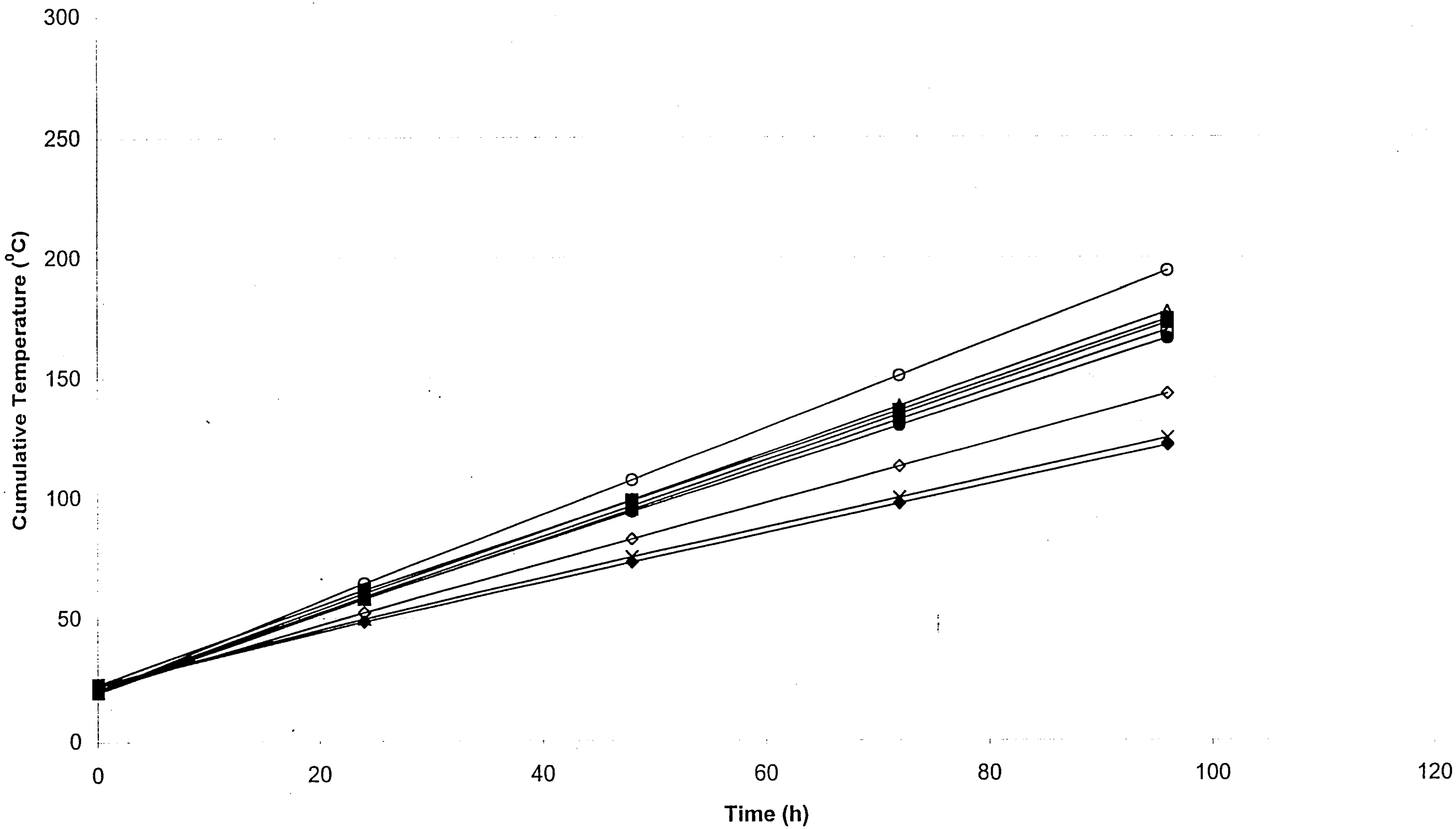
(■) Internal roof (7)

(◇) Internal floor (8)

(◆) External room temperature 1

(×) External room temperature 2





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Cumulative Temperature (^{0}C)
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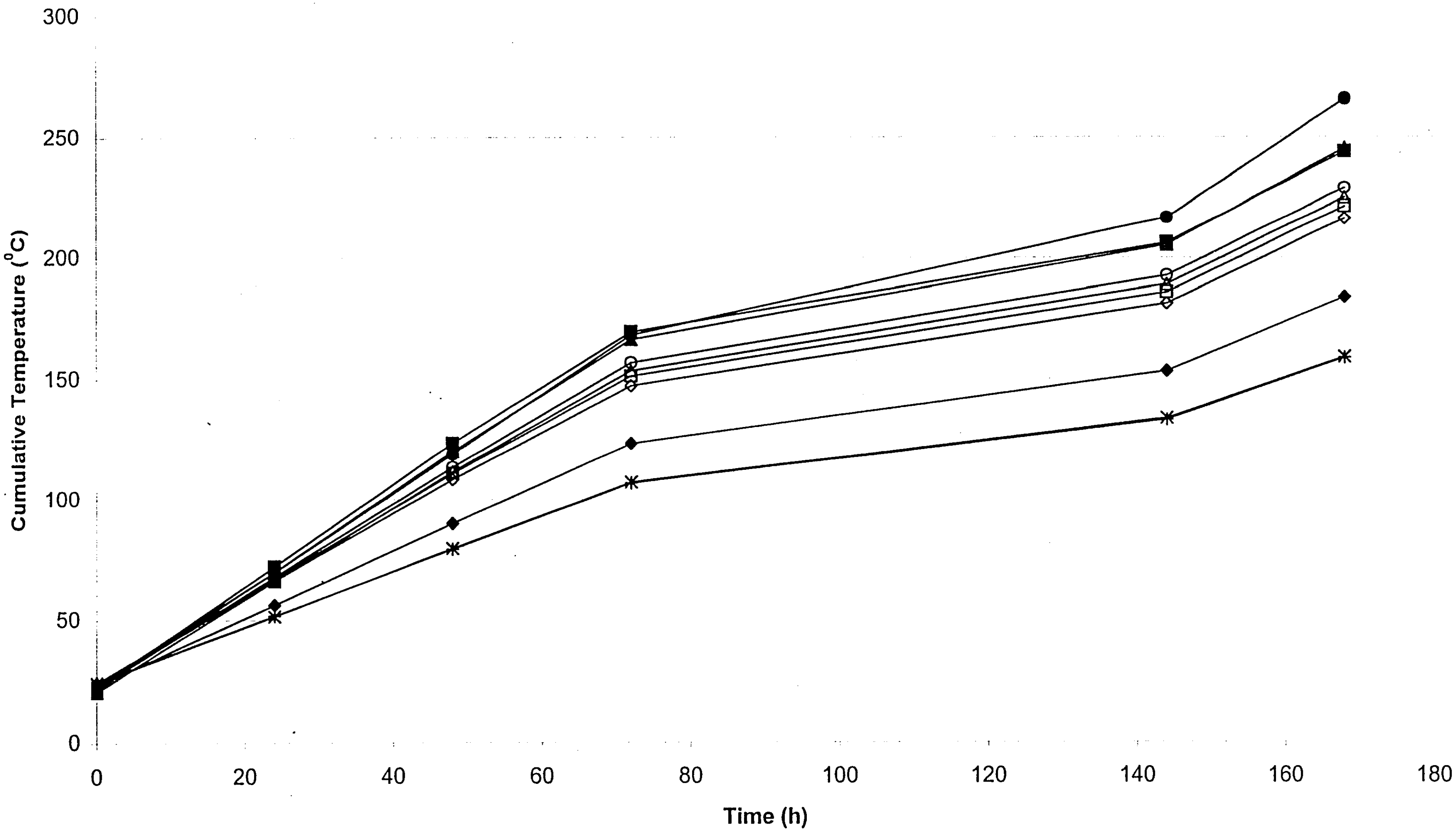
120
Time (h)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Cumulative Temperature (^{0}C)
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Time (h)

Figure 54: Physical compost model green waste feedstocks Trial 2 (autumn derived waste). Cumulative temperature (°C) over time (h). Model operational parameters set at, heating coil 65°C, cooling coil 15°C and air 5 l min^{-1}. Diagram indicates positions of the thermocouples within the model.

(○) Surface (1)

(△) Right hand upper front (2)

(□) Left hand upper front (3)

(●) Middle (4)

(▲) Right hand lower back (5)

(■) Left hand lower back (6)

(◇) Internal roof (7)

(◆) Internal floor (8)

(×) External room temperature 1

(+) External room temperature 2

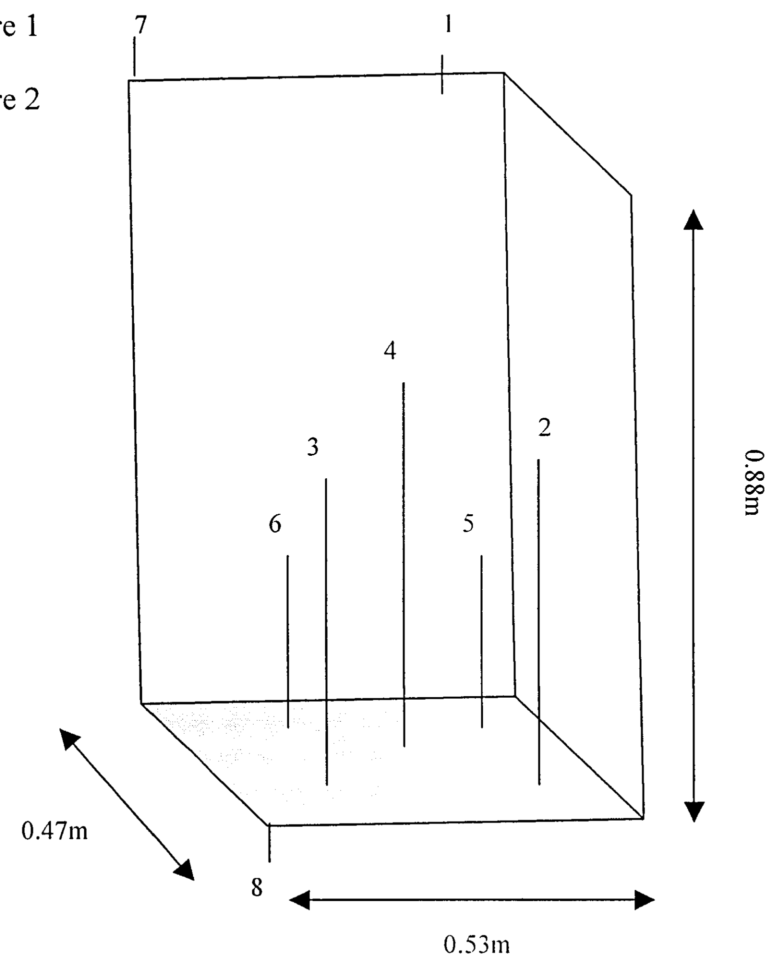


Figure 55: Physical compost model green waste feedstocks Trial 3 (autumn derived waste). Cumulative temperature (°C) over time (h). Model operational parameters set at, heating coil 65°C, cooling coil 15°C and air 5 l min^{-1}. Diagram indicates positions of the thermocouples within the model.

(○) Surface (1)

(△) Right hand upper front (2)

(□) Left hand upper front (3)

(●) Middle (4)

(▲) Right hand lower back (5)

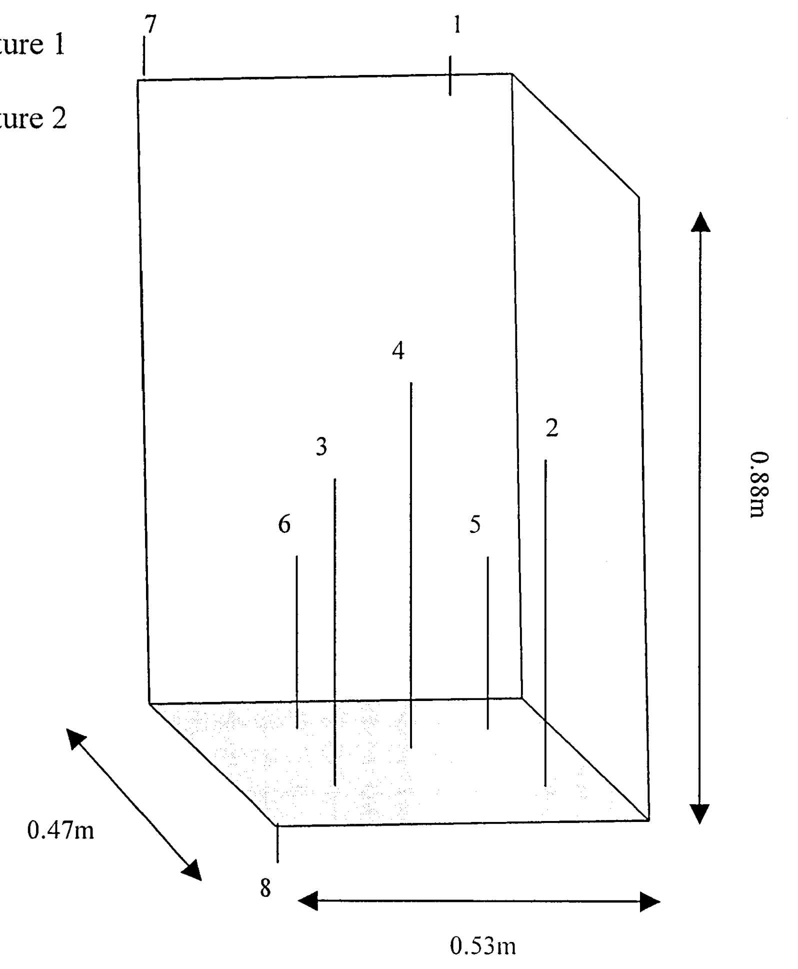
(■) Left hand lower back (6)

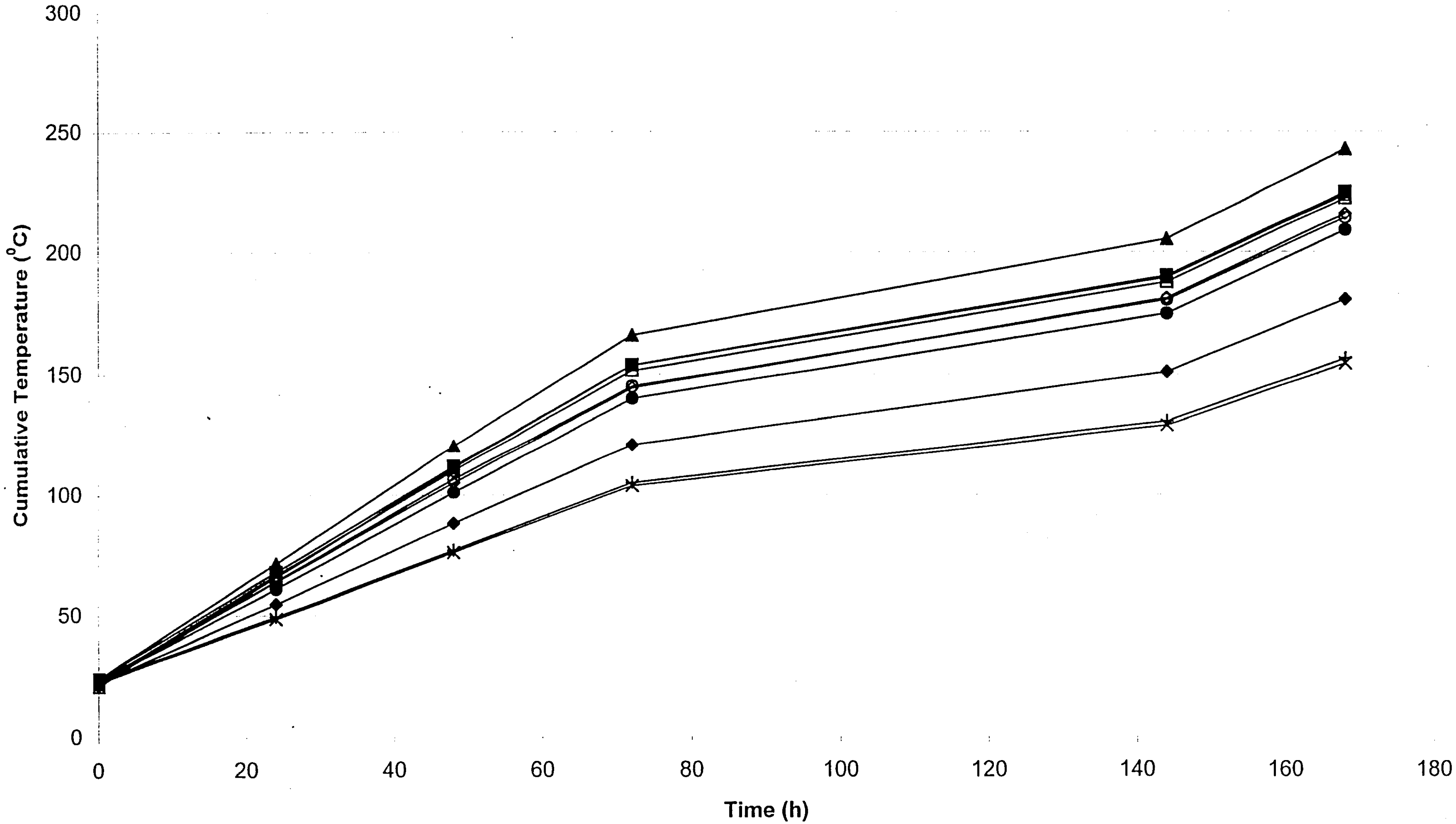
(◇) Internal roof (7)

(◆) Internal floor (8)

(×) External room temperature 1

(+) External room temperature 2





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Cumulative Temperature (°C)
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Time (h)

Therefore, some form of internal heating was required to overcome this. The introduction of mild heating within the core region of the composting chamber was designed to stimulate increased microbial activity, and thereby, allow the natural development of thermophilic temperatures and the composting process. The data presented from the green waste experiments indicates that this is possible. The presence of hot spots within a newly established windrow, where heat seems to radiate out (both directly and indirectly), were shown in the field trial experiments and these appeared to encourage the development of widespread temperatures elevated *via* increased microbial activity. Therefore, the presence of the heating coils in an attempt to remedy the physical limitations of the waste capacity of the model, can be likened to such activity within a large-scale windrow system.

The overall cumulative temperature trends within the green waste trials (Figures 54 & 55) were very similar. This indicates that general temperature development with the model windrows was essentially the same and reproducible. However, it can be noted that although overall cumulative temperature trends were similar, the distribution of heat exhibited some variation. This is inline with field based observations whereby the distribution of temperature was non isothermal. It was demonstrated that there could be hot and cool regions simultaneously within a particular layer of a windrow and the location of these zones varied between trials.

PHYSICAL AND CHEMICAL ASSESSMENTS

A range of physical and chemical tests were used to profile the green waste feedstocks used within the physical model. A summary showing the range of value of these physical-chemical parameters is presented in Table 4. The values are typical and representative of main season, (i.e. late spring to early autumn), urban green waste derived from gardening type sources before undergoing windrow-based composting, and can be compared with the data from the field trials. Bulk density was low (255 to 416 g l^{-1}) reflecting the coarse nature of this material, and also the open structure of the starting material. Conductivity

Table 4: Physical and chemical characteristics of shredded urban green waste used as feedstocks in physical compost model trials. The data represent the mean range of values, Day 0 (upper) and Day 7 (lower) found for each parameter (Column A) with comparative values from Field Trial 1 (winter) and 2 (summer) (Column B).

	A: Compost Model	B: Field Trial 1 and 2
Bulk Density (g l^{-1})	255 to 416	288 to 351
Conductivity (μS cm^{-1})	1942 to 2030	483 to 1991
Moisture Content (%)	53.5 to 59.5	38.7 to 44.7
Organic Matter Content (%)	56.2 to 76.2	59.5 to 82.6
pH	6.90 to 7.01	6.43 to 7.30

Bulk Density (g l^{-1})	416	No data
Conductivity (μS cm^{-1})	1253	423 to 1882
Moisture Content (%)	39.6 to 47.8	30.1 to 45.7
Organic Matter Content (%)	63.0 to 70.8	57.6 to 72.0
pH	7.36 to 7.40	6.92 to 7.29

values were moderately high (1942 to 2030μS cm^{-1}) (cf. the summertime established field trial, 1991μS cm^{-1}). This is indicative of the nutrient-rich properties of the types of waste generally available at that time of year. It is suggested that the simulation of heavy rainfall within the model would result in a leachate with potential for environmental impact when using such a feedstock. Moisture content (53.5% to 59.5%) was within the range recommended as acceptable for composting (40% to 60%) and was relatively high, reflecting the fresh-green nature of the feedstocks available during this season. Organic matter content is typical of newly shredded feedstocks, and the range from 56% to 76% describes well the varied composition of main season green waste, with a mix of soft-green materials as well as woodier items being present. This can be compared to a wintertime feedstock, which generally has a greater percentage of woody waste and high organic matter content, often with low bioavailability.

The pH values for the waste were very much the expected for waste of this type, being around neutral. The evidence provided by the physical and chemical assessments shows that the green waste feedstocks represented not only typical material, but also material with characteristics that are generally considered to be within an ideal range for composting (Rynk and Richard, 2001; Day and Shaw, 2001). The use of such wastes within the experiments was vital in the development of the model, because they provided the optimal conditions for both the stimulation and simulation of the microbial activity of the composting process, which is essential in the initial stages of the design and development of a novel model. The presence of variables, such as extreme moisture content etc, would have added unnecessary complications to the operation and testing of the basic model concept.

ADVANCEMENT OF PHYSICAL MODEL DESIGN

Until now physical models (laboratory or bench scale composters) have been designed around the concept of in-vessel or chemostat style systems. Although many of these models have clearly been of value in the development of improved operational practices and the advancement of composting science, there are a number of weaknesses in current designs. The lack of field trials before or after the design of a model and the reliance upon laboratory and pre-existing data without independent verification for example are such problems. It is clearly important that during the development of a realistic model, that characteristics and behaviour observed in the field (i.e. the full sized system) are considered and simulation of these characteristics is incorporated into the model operation. A valid model must copy the field situation, not produce an alternative form of composting. The design of the novel physical model presented in this study was heavily based upon information derived from field based experimental composting trials of urban green wastes. Knowledge of the behaviour of "*real*" composting systems is of advantage when constructing a model system. This has allowed phenomena observed in the operation of the model to be linked to situations seen in the field trial data, and thereby, provide validation of model characteristics as being similar to *in vivo* windrow composting systems.

Unlike other physical compost models, the overall objective of this study was not to simply produce a small-scale version of a generic composting process, but rather to design a system that specifically targeted open-windrow based composting. A small-scale model of such a method would allow detailed analysis and assessment of the behaviour of windrows, thus providing information for the improvement of this valuable sustainable waste management technology. As windrows are not contained, but are open in the environment, the feedstocks were contained within an open cage (to provide only "windrow structure") with an open space around them, and within this gap between the cage and the main model wall, were placed a system of cooling coils. These coils were designed to simulate the outside environment. Experimentation showed that this approach affected the propagation of thermophilic temperatures with the model windrows. Although a negative effect in terms of the sustainability of thermophilic composting, this action was similar to what was seen in parts of field trial windrows exposed to the effects of wind chill.

Windrows are not heated artificially in the field, heat being generated and retained within the structure because of intense natural microbial activity and the insulating properties of the large volume of waste material itself. In a small-scale system, there are difficulties associated with the establishment and maintenance of elevated temperatures within a limited volume of material. The traditional approach to this problem has been the provision of a thick insulating jacket directly around the reaction vessel. Additionally, external heating has been used, either in the form of water baths, in which the chamber sits, or direct heating inside the vessel. The main aim of such systems was to heat the waste up to thermophilic temperatures and therefore, create conditions suitable for thermophilic microbial growth. None of these methods is realistic in terms of natural windrow behaviour. Therefore, the model presented in this study used a method whereby water-filled heating coils were placed within the core region of the feedstocks (microbial heat is mostly generated and retained within the interior of a windrow not the outside). These were used to provide background heating, in order to assist in the natural development of thermophilic conditions by providing an initial "*helping hand*" to the microorganisms. The results from the experiments using the model indicate that this was a practical system. Data showed that after a period of 24 hours (a lag phase where conditions within the model were becoming optimized) temperatures trends, including cumulative temperature, demonstrated increased thermal activity over microbially inert feedstocks, which had established a lower steady-state condition. Evidence suggests that the heating system within the first 24 hours provided sufficient mild heating and combated heat loss to allow the development of increased mesophilic microbial activity leading to the elevation of temperatures within the feedstocks. This is inline with typical behaviour within a compost system, where the initial rise in temperature is caused by the mesophilic population before succession to the thermophilic community.

CONCLUSIONS

The novel physical compost model presented in this study was shown through experimentation to partially describe the initial behaviour of a open windrow composting system, in terms of the simulation of the mesophilic microbial production of heat within the feedstocks (the non-isothermal distribution of this heat is observed also) leading to the development of thermophilic temperatures. The decline in temperatures after the mesophilic period is indicative of the time of the first microbial succession inside a field scale windrow, when thermal inactivation of the mesophiles has occurred and the thermophilic community is not yet fully established. Pressure for heat loss was increased *via* the cooling coils and this clearly prevented the development of a second temperature peak caused by thermophilic microbial activity. However, it has been shown to occur in the field, and therefore demonstrates the value of having an environmental control system built into the model, further enhancing its realism to windrow conditions. It has been shown in this study that a practical, economic and functional physical compost model designed around the open windrow method can be constructed and trialled successfully to produce basal data inline with that assessed in the field trial situation.

CHAPTER 5 - PARALLEL GREEN WASTE COMPOSTING TRIAL OF PHYSICAL MODEL AND FIELD WINDROW

INTRODUCTION

A novel physical composting model was developed and tested, the results of which were presented in Chapter 4 of this study. This model uniquely modelled not a generic or in-vessel composting process, but rather the popular and versatile open windrow method. The development and design of the model was based largely on data derived from comprehensive field trial investigations of temperature trends and physico-chemical behaviour within typical urban green-waste windrows. The data derived from the experiments using the model showed that the system was capable of producing temperature trends and distributions having similarity with characteristics observed in both the winter and summer field trials. Particularly the initial phase of the composting process (i.e. mesophilic derived temperature increases followed by decline, before the succession to thermophilic activity).

Therefore, having established that the physical model was capable of mimicking some of the basic characteristics of windrow composting, additional experimentation was required to further develop and prove the model. To this end a parallel trial was envisaged, whereby both the physical model and a field trial windrow would be established from the same materials and run at the same time and the development and distribution of temperature would be closely monitored. By this method a direct comparison could be made between the thermal activity observed in the field-based windrow and that seen in the model windrow. This would further the advancement of the novel physical model, because unlike previous model experiments, which used green waste similar to that utilized in the earlier field trials, this one would employ the same materials at the same time.

Experimental Rationale

An experimental composting trial was designed, whereby a field-scale windrow was established and using the same urban green waste feedstocks, the physical model was loaded and run. Both were then monitored in terms of temperature development and distribution for a period of approximately ten days. Such a timespan represents the initial period of composting simulated by the physical model system. This allowed direct comparison between *in vivo* and *in vitro* composting systems.

METHODS

FEEDSTOCK PREPARATION

Seasonally available urban green waste was diverted from Dundee City Council's Discovery Compost programme and shredded at the Council's Environmental and Consumer Protection Department's composting site at Riverside, Wright Avenue, Dundee, UK, using a TIM SD2000 shredder (Tim Maskinfabrik A/S, Fabriksvej 13, Denmark). The material comprised botanical wastes derived from Council civic amenity sites, citywide compostainer collections and commercial gardeners and landscapers. Immediately after preparation this material was used either in the construction of the field trial windrow or bagged and transported to the laboratory for use in the physical model.

FIELD TRIAL WINDROW TEMPERATURE MONITORING SYSTEM

Individually numbered PVC coated 2m long Type K thermocouples (Kalestead Ltd., Braintree, Essex, UK) were attached to 2.14m long bamboo garden canes at varying distances along the length of the cane *via* plastic cable ties. Three layers with thermocouples positioned thus; Layer 1, 0.5m high; 1m deep, Layer 2, 1m high; 0.5m and 1m deep and Layer 3, 1.5m high; 0.5m deep were employed. Resulting in a total of 60 thermocouples. Each layer consisted of 10 canes equally spaced (lengthwise) along the windrow. Details of the thermocouple arrangements are presented with Figures 61 to 63.

WINDROW CONSTRUCTION

A Liebherr 531 wheeled loader (Liebherr-Werk Bischofshofen GmbH, Bischofshofen, Germany) was used to prepare a windrow in the manner outlined in the methods section of Chapter 3. The windrow (approximate dimensions; 10.5m long, 3.5m wide and 2m high) was constructed along a north-south alignment at the Riverside composting site during November 2001. Plate 2 shows the completed windrow shortly after establishment.

RECORDING OF WINDROW TEMPERATURES

Once the windrow was constructed and the thermocouple end plugs cleared of any feedstock debris, temperature readings were taken from each of the thermocouples, to establish zero time (day 0) temperature readings. Daily temperature readings were taken (Monday to Friday mornings) and logged in the manner outlined in the methods section of Chapter 3.

PHYSICAL MODEL TRIAL ESTABLISHMENT

After the urban green waste was shredded, a proportion of the material was bagged and transported to the laboratory. There was a period of approximately 4 hours between shredding and the establishment of the physical model trial. The waste material was then loaded by the handful, to reduce compaction, into the composting chamber of the physical model. Operating parameters were an output temperature of 15°C for the cooling coil and an output temperature setting of 65°C for the heating coil arrangement. Moist aeration was supplied to the unit at a rate of 5 l min^{-1}. All parameters were delivered in a constant manner over the period of the experimental run. Thermocouples were arranged as indicated

Plate 2: Parallel Running Trial (November 2001) Field Trial Windrow at Riverside composting site shortly after establishment, looking north-east.

in Chapter 4 of this study. Temperature assessment was made immediately after the start of the experimental run and on a regular basis throughout the trial using the methods indicated in Chapter 4.

RESULTS AND DISCUSSION

OVERALL TEMPERATURE TRENDS WITHIN FIELD AND MODEL WINDROWS

Figure 56 shows the mean temperature data from both the field and model windrows along with the respective air (ambient) temperatures over the period of the trial. It provides a direct comparison of the thermal activity between the two systems when using the same source feedstocks at the same time. There were clear similarities between the two systems, particularly in the earlier stages of the trial. It can be noted that both systems reached thermophilic temperatures within 24 hours of establishment. This indicates that when the shredded waste was positioned within a structure (e.g. a windrow) conducive to increased microbial activity, the mesophilic population showed a rapid increase in metabolism that resulted in the upward trend in temperature. The rapidity of the rise in temperature in both systems (with no clear lag phase) suggests that a combination of high quality (in terms of nutrients and structure) feedstocks and highly active microbial population were present. The mean temperature in both windrows was very similar at the 24 hour time period. This demonstrates that activity within both systems was closely related, and provides evidence that the model was capable of simulating the behaviour seen in a field-scale windrow. The data show that the model was able to produce characteristic thermophilic temperatures within 24 hours following establishment. The gaining of such temperatures within the model system is vital for the realistic simulation of windrow based composting activity.

After 24 hours the field windrow mean temperature continued to increase for a further 24-hour period before peaking. The model windrow stabilized during this time period. The

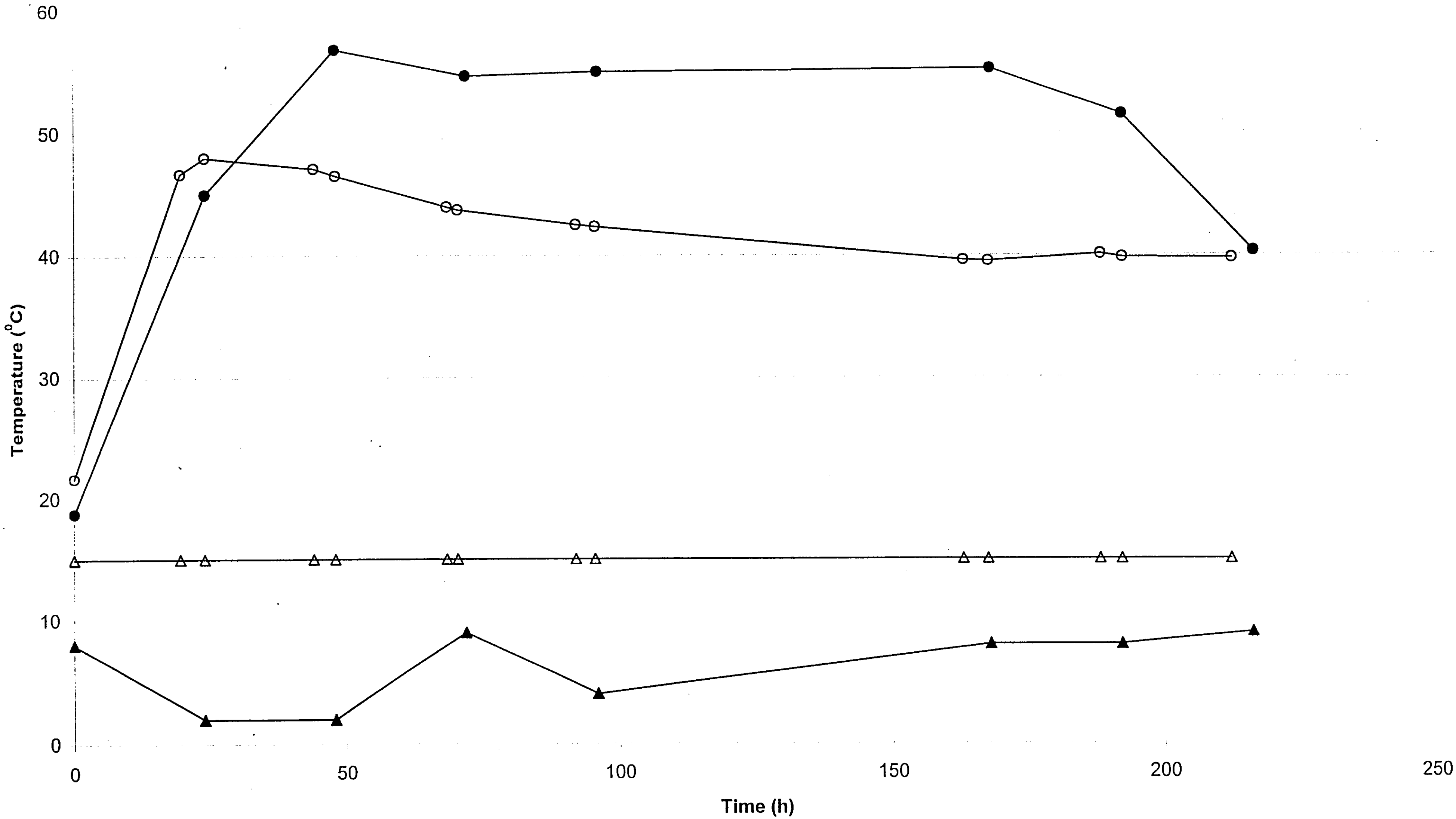
Figure 56: Parallel running trial (November 2001). Physical model mean compost temperature (°C) and mean field trial overall windrow temperature (°C) with related air temperatures (°C) shown over time (h).

(○) Physical model mean compost temperature

(●) Field trial mean windrow temperature

(△) Physical model air temperature

(▲) Field trial air temperature



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Temperature (^{0}C)
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250
Time (h)

higher mean temperatures exhibited within the field windrow reflect the larger volume of material, which was able to produce and retain a greater level of heat than the limited mass contained inside the model. Such differences between the two systems are, at this stage in the design of a novel physical composting model, not particularly important. The general trends of and distribution in temperature are the more vital parameters. It can be noted that after the initial temperature peak in both systems there was a decline in temperatures, probably representing thermal inactivation of parts of the mesophilic population. This decline in temperature continued in the case of the model (this was consistent with previous model experimentation) and reflected the model's current lack of ability to effectively retain enough heat to allow the establishment of a thermophilic population. The downward pressure placed upon it by the small volume of feedstocks and the cooling coils / aeration representing the external environment clearly limit the model in this aspect. However, both these factors (small size and windspeed) are parameters that influence the behaviour of composting systems in the field and therefore, could be considered to be realistic reflections of windrow composting in the model design.

Following the short period of temperature depression in the field windrow, a phase of temperature stabilization occurred, when a mean temperature of approximately 55°C was recorded for an extended time (cf. the 24 to 48 hour plateau period of the model). The larger volume of this windrow allowed the development of a sustained thermophilic population. At 168 hours there was a defined downward trend in the mean temperature of the field windrow, and at the same time the decline in the model mean temperature ceased. This continued until the end of the trial, when both model and field windrow mean temperatures were similar (approximately 40°C). This suggests physical or chemical changes in the nature of the feedstocks (e.g. compaction *via* slumping or exhaustion of a nutrient source) as the major cause of this temperature decline. Both could lead to less favourable conditions for rapid exothermic microbial metabolism either as oxygen-limited or water-logged conditions developed or nutrient exhaustion resulted in a succession phase before the establishment of another group of microorganisms more suited to the prevailing conditions. However, over-plotting of the mean field windrow temperature with mean windspeed data shows an interesting trend (Figure 57). There was a dramatic increase in windspeed from around 3MPH to 18MPH during this period of temperature decrease. This suggests that the main cause of the fall in temperature was windrow cooling *via* increased windspeed. The earlier low (falling) windspeed recorded at the start of the trial allowed the sustained development of thermophilic temperatures. This concurs with earlier field trial data discussed in Chapter 3 of this study. The effects of increased windspeed on windrow temperatures can be compared to the heat loss within the model system *via* the environmental simulation system. In effect, the model represented a condensed version of events seen within the field trial situation. The data presented in this study shows that when attempting to model the open windrow composting process, it is vital that the effects of windspeed are taken into consideration. Current physical composting models being based on in-vessel designs do not do this and therefore, extrapolation of these models to other forms of composting systems (e.g. windrows) is flawed.

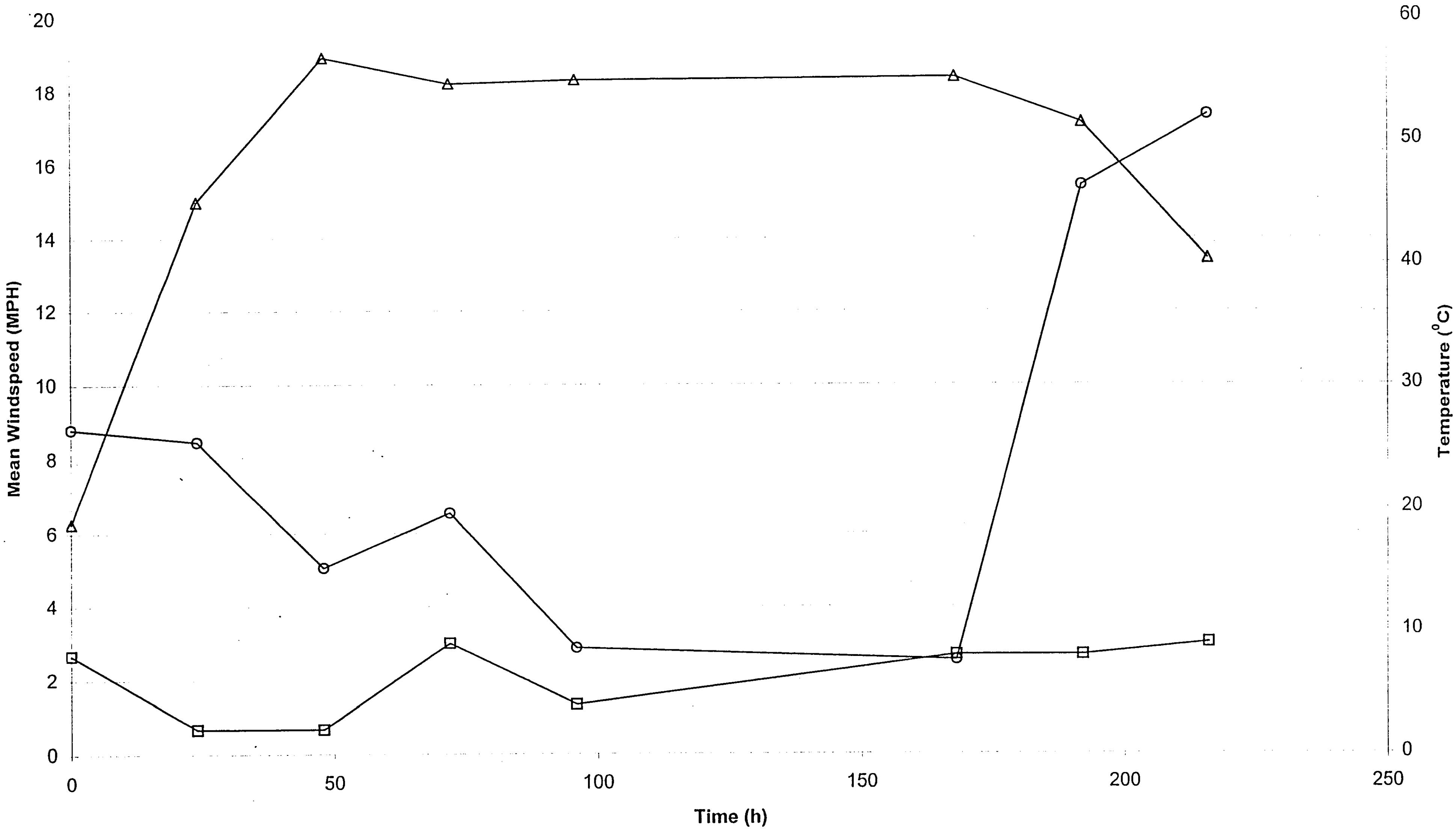
The air temperatures (Figure 56) for both trials showed no linkage to the temperature of the feedstocks or the windspeed. Although the air (ambient) temperature recorded for the field trial was constantly below 10°C, this did not prevent the development of elevated temperatures. The changes in air temperature were not matched by changes in windrow temperature as had occurred with varying windspeed.

Figure 57: Riverside composting Field Trial 3 (November 2001) (parallel running trial). Mean windspeed in Miles Per Hour (MPH) and overall mean windrow temperature (°C) with ambient (air) temperature (°C) over time (h). Windspeed data was derived from information provided by the Dundee Airport weather station (National Weather Service, Internet Weather Source, Current Weather Conditions – Dundee / Riverside, United Kingdom: http://weather.noaa.gov/weather/current/EGPN.html) adjacent to the composting site.

(○) Mean windspeed (MPH)

(△) Mean windrow temperature

(□) Ambient (air) temperature



Mean Windspeed (MPH)
20
18
16
14
12
10
8
6
4
2
0
0
50
100
150
200
250
Time (h)
Temperature (°C)
60
50
40
30
20
10
0

DETAIL OF WINDROW TEMPERATURE TRENDS AND DISTRIBUTIONS

Figure 58 displays a detailed picture of temperature development within the physical model during the parallel running trial. In comparison, Figure 59 shows the comparative data for the field trial (i.e. individual temperature plots from all operational thermocouples arranged by geographic quarters (NE, NW, SE, and SW) to illustrate the gross temperature patterns during the trial). The data presented in Figure 58 shows that all areas of the model windrow quickly increased in temperature over the first 24 hours of the trial and all areas (apart from the surface) reached thermophilic conditions during this time. Initially a fairly broad band of temperatures was exhibited within the feedstocks, with temperatures ranging from around 45°C to 55°C. This can be compared with the data observed in Figure 59, where during this period there was a wide range of temperatures recorded within the windrow. Figure 58 shows that peak temperatures within the model were not that dissimilar to the overall mean temperatures observed in the field windrow. In terms of model development this is most encouraging. The data demonstrate widespread thermophilic temperatures existed within the model until between 72 and 96 hours, and it was only after this point that most regions of the model windrow drop in temperature, exhibiting a narrowing of the temperature ranges. Only the middle (core) section continued to display thermophilic temperatures. This probably reflected the thermally protected and enhanced nature of this area of the model windrow and is representative of the innermost regions of a typical windrow. The temperature trends for the surface of the model windrow were lower than the feedstock material. This is expected and is reflective of the fact that the outermost layer of a windrow is the area where the least amount of exothermic microbial activity is expected to occur and where the greatest heat loss and influence by external factors is likely to take place. This fact is important when considering physical composting model design. Many existing models employ some form of external heating, typically a temperature controlled waterbath in which the composting vessel is submerged, to both generate heat within the

Figure 58: Physical compost model parallel running trial (November 2001). Model windrow temperature changes (°C) with time (h). Model operational parameters set at, heating coil 65°C, cooling coil 15°C and air 5 l min^{-1}. Physical compost model environmental simulation system temperature shown. Diagram indicates positions of the thermocouples within the model.

(○) Surface (1)

(△) Right hand upper front (2)

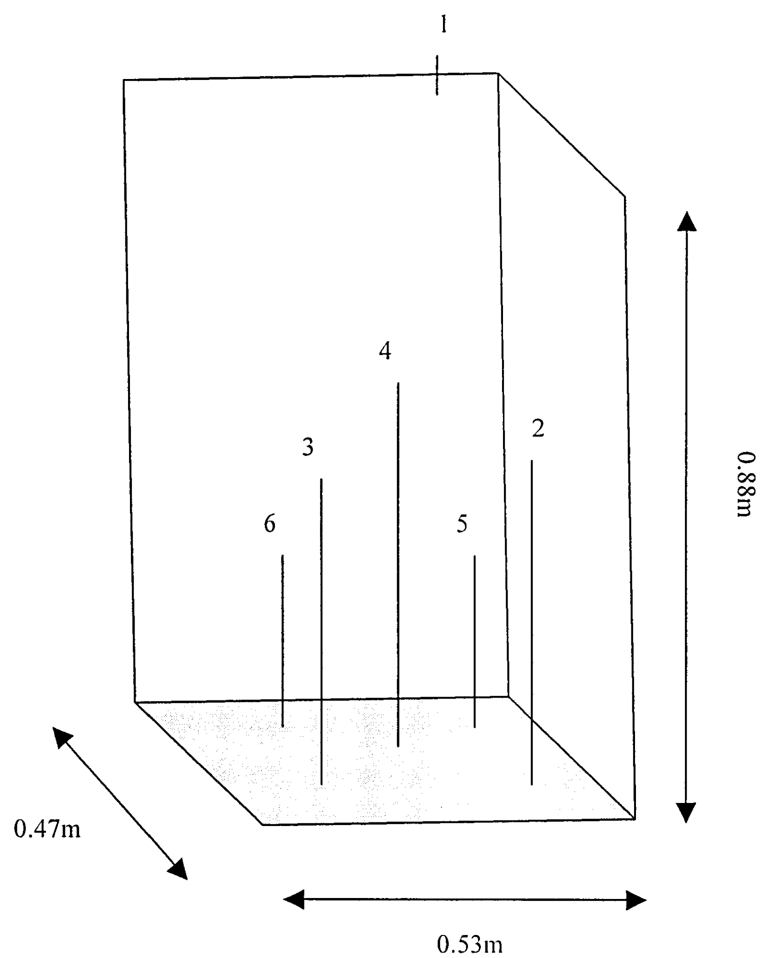
(□) Left hand upper front (3)

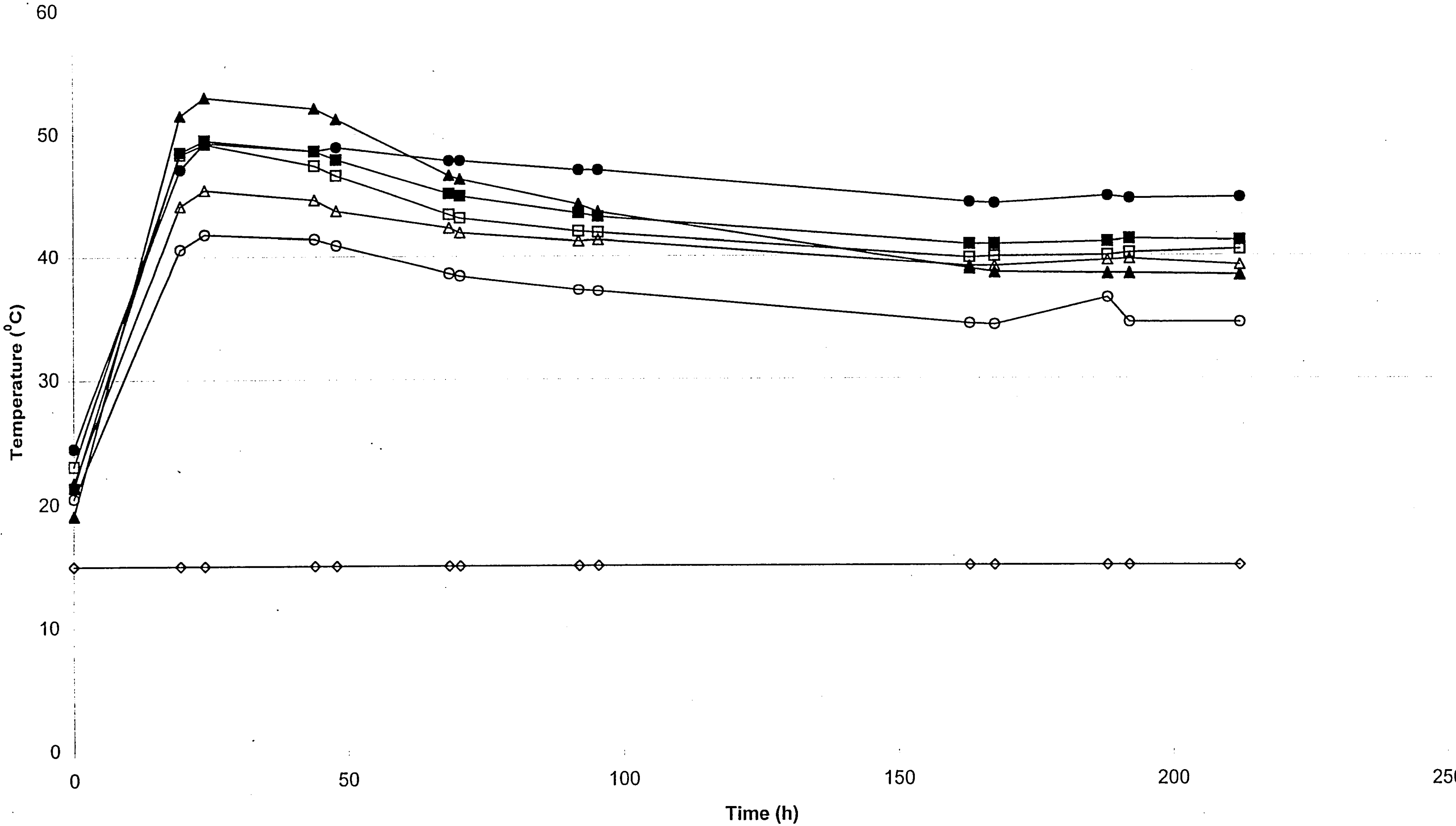
(●) Middle (4)

(▲) Right hand lower back (5)

(■) Left hand lower back (6)

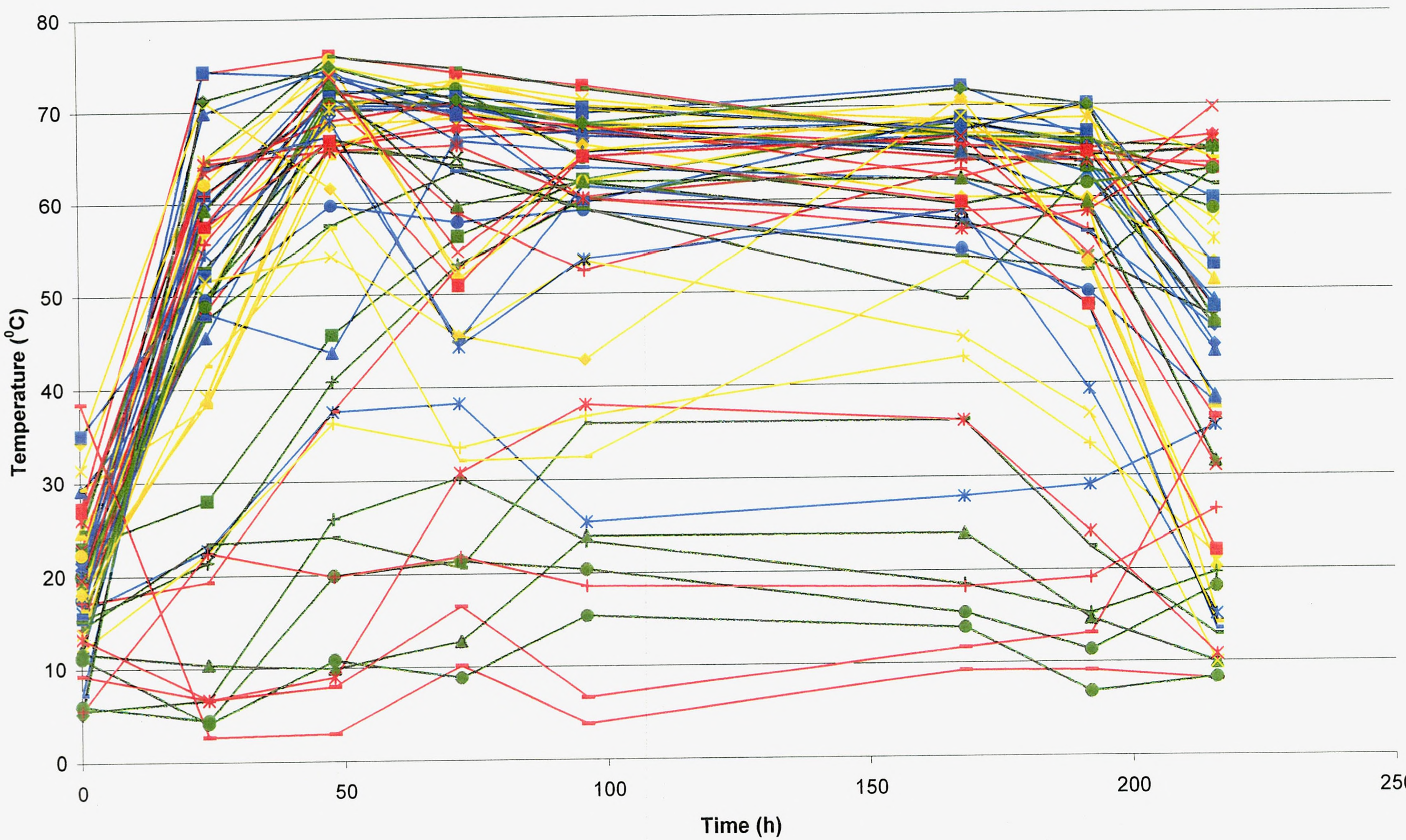
(◇) Environmental simulation system temperature





60
50
40
30
20
10
0
Temperature (°C)
0
50
100
150
200
250
Time (h)

Figure 59: Riverside composting Field Trial 3 (November 2001) (parallel running trial) windrow temperature plots (°C) over time (h). Temperature trends from all operational thermocouples on an individual basis are presented. The graph is employed to indicate the gross temperature patterns and fluctuations therein within the windrow over the period of the field trial. The temperature plots have been arranged by geographic quarters (NW, NE, SW, and SE). The following colours have been used to represent the windrow regions: Blue (NW), Red (NE), Yellow (SW) and Green (SE).



80
70
60
50
40
30
20
10
0
Temperature (°C)
0
50
100
150
200
250
Time (h)

feedstocks and limit heat loss from them. Therefore, this results in the feedstocks being heated from the outside, which suggests a windrow with lots of exothermic microbial activity and elevated temperatures on the surface of the structure. Clearly this is not the case, the greatest and most sustained temperatures are generated and retained mainly in the interior of the windrow. The field trial data presented within this study have repeatedly shown this to be the case. This flaw in the design of such models must certainly limit their functionality as general models of the composting process. The novel physical model presented in this study was designed with this factor in mind and experimental trials have produced data which show that heat generation was limited to the inner regions of the composting mass and the surface areas remained cooler and reflected the outside air temperature of the model system. The purpose of the use of an insulated box, such as a freezer unit, was not to prevent heat loss from the composting mass, but rather to allow the creation of a micro-climate within the box, which could simulate the characteristics of a urban green waste derived windrow situated on a typical out-of-doors composting site.

EXAMINATION OF FIELD WINDROW TEMPERATURE BY LAYER

Figure 60 shows the mean temperature profiles for each of the three thermocouple layers within the field windrow together with the ambient temperature. Layers 1 and 2 exhibited the highest temperatures, clearly within the thermophilic zone. Layer 2 at 1m high initially showed the faster increase and greater mean temperatures. After approximately 72 hours there was little difference between the mean temperature of either Layer 1 or 2 (exhibiting mean temperatures in excess of 60°C). Latterly, Layer 1 (0.5m high) displayed a slower decline in temperature and retained a higher mean temperature at the end of the trial than Layer 2. Layer 3 (1.5m high) showed a quite different temperature profile, with mean temperatures only reaching on average around 40°C. Such stratification of temperature clearly has implications of the effectiveness of pathogen kill within the windrow. Overall

Figure 60: Riverside composting Field Trial 3 (November 2001) (parallel running trial). Windrow temperatures (°C) are described by reference to mean temperatures at three heights termed layers where thermocouples were positioned at varying depths, additionally the ambient (air) temperatures (°C) are given for the period of the trial.

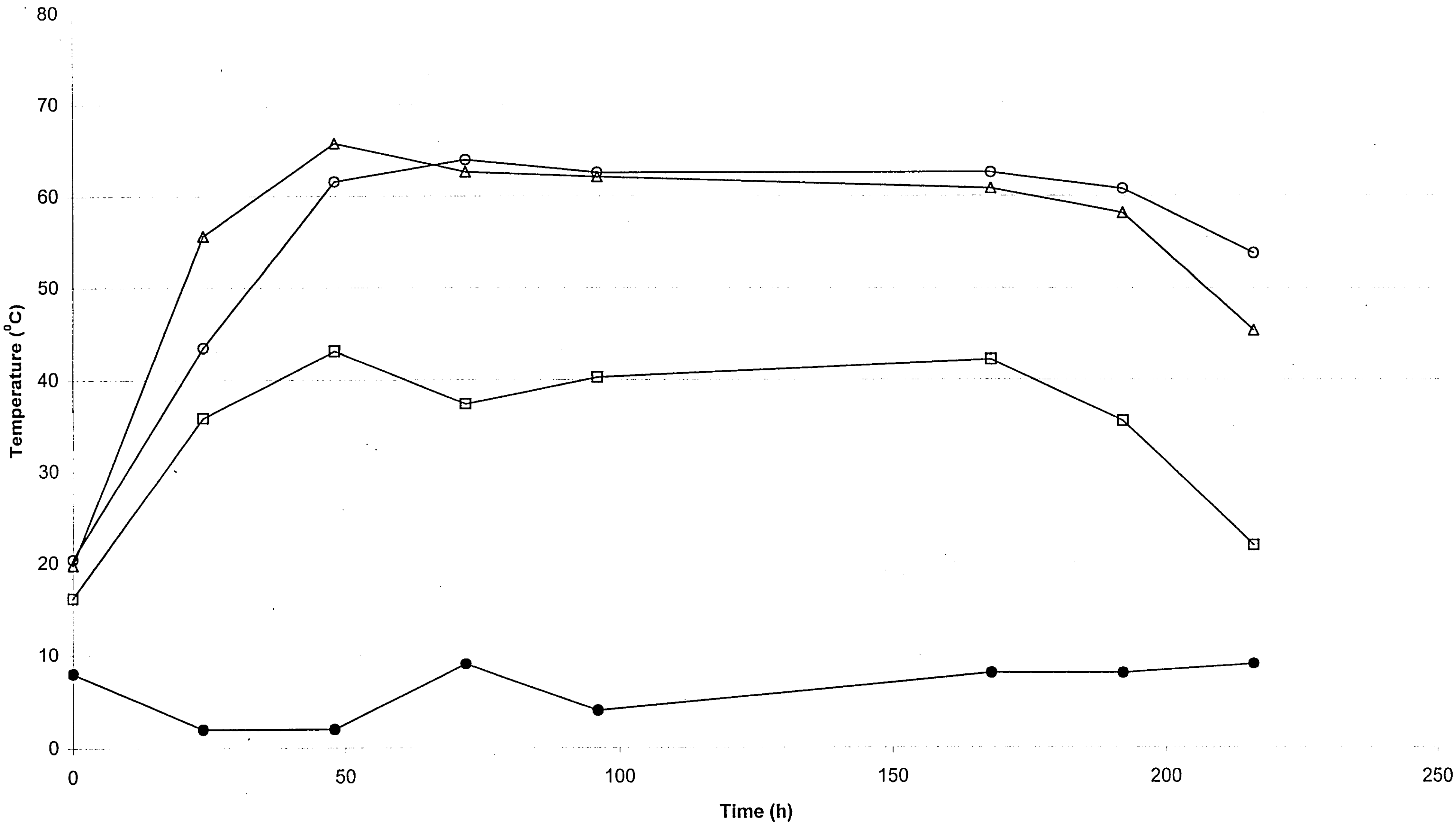
Layer 1 indicates temperature readings from a height of 0.5m and a depth of 1m. Layer 2 indicates temperature readings from a height of 1m and depths of 0.5m and 1m. Layer 3 indicates temperature readings from a height of 1.5m and a depth of 0.5m.

(○) Layer 1 mean temperatures

(△) Layer 2 mean temperatures

(□) Layer 3 mean temperatures

(●) Ambient (air) temperature

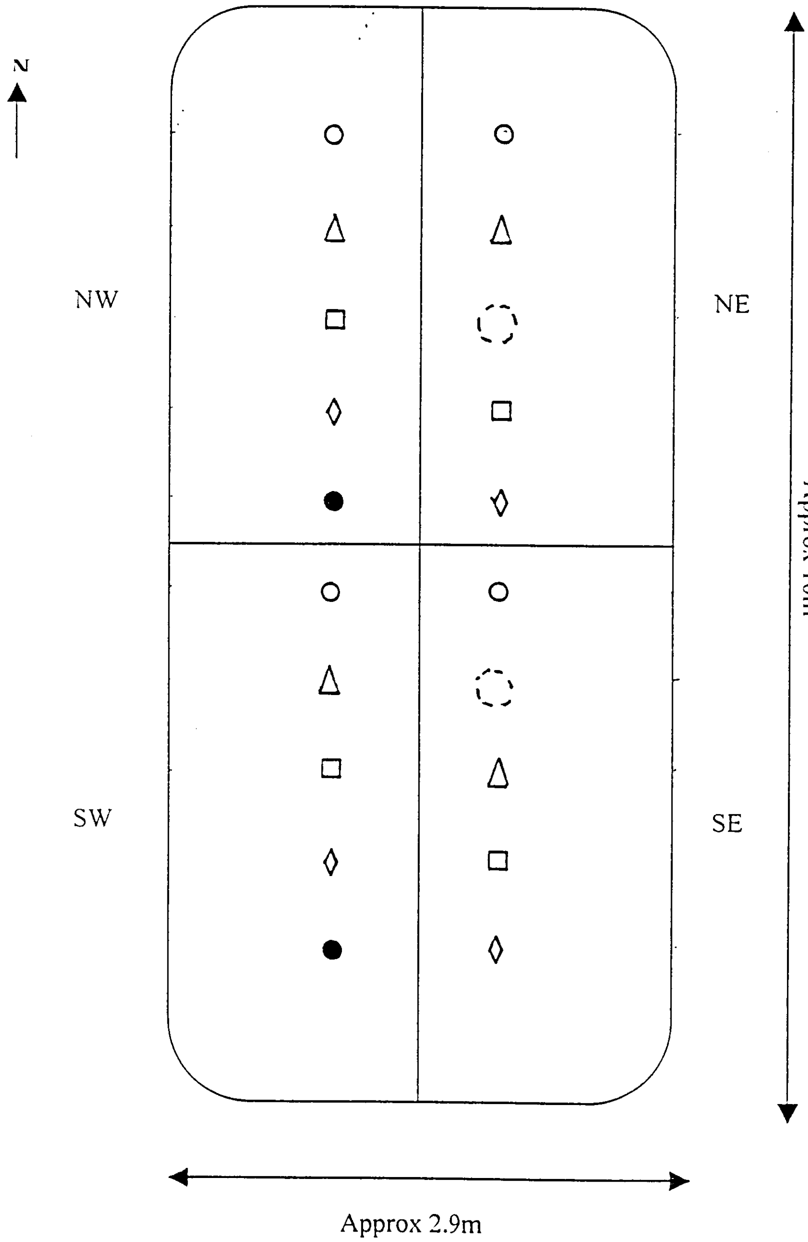


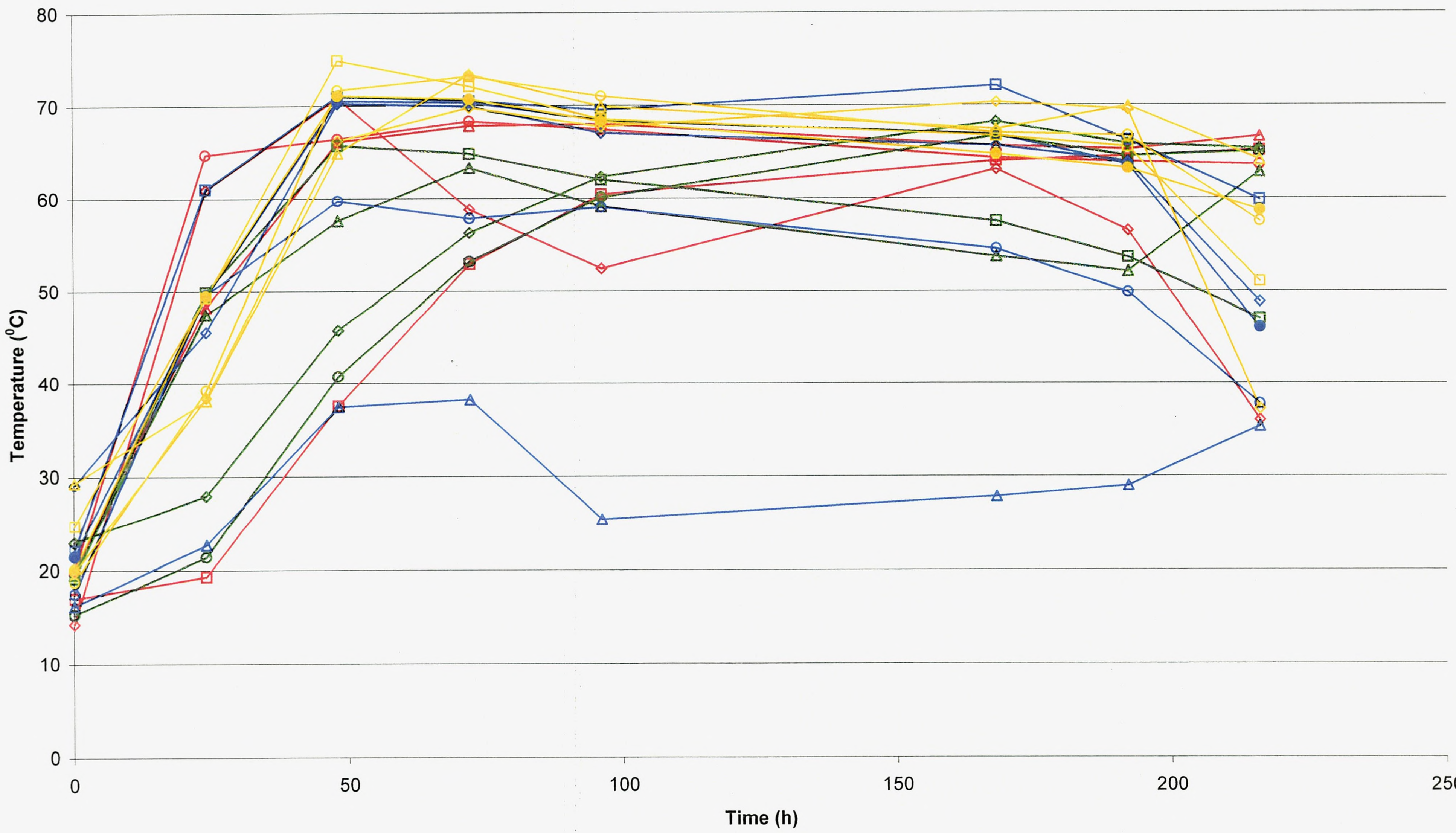
80
70
60
50
40
30
20
10
0
Temperature (^{0}C)
0
50
100
150
200
250
Time (h)

mean temperatures (Figure 56) imply that windrow temperatures were sufficiently high and prolonged to efficiently reduce pathogens (Table 2). However, the data presented here showed this not to be the case. This reinforces the necessity of detailed temperature monitoring and good windrow management to ensure effective potential pathogen reduction. The results (Figure 60) clearly show that areas of a windrow with greater cross-sectional mass are able to obtain and sustain much higher temperatures than areas with less overall volume. In many ways the mean temperature trend exhibited by Layer 3 of the field windrow was similar to the mean temperature behaviour of the model windrow (Figure 56). This is reasonable, because both represented smaller, limited depth collections of feedstocks. Both had greater difficulty in maintaining thermophilic temperatures and were subject to increased heat loss *via* external influences than large masses of feedstocks.

Figures 61, 62 and 63 give a detailed picture of temperature trends within each field windrow layer and have been arranged to reflect height, depth and physical location (NE, SE, NW, SW) within the windrow over the period of the trial. Layer 1 (Figure 61) and Layer 2 (Figure 62) showed strong similarities as expected. The data does reveal in more detail the differences, particularly, between the two layers. Layer 2 exhibited a uniformly steeper, more linear rise in temperature during the first 48 hours of the trial, while Layer 1 showed a more mixed response. This suggests that the waste material located around 1m high was initially the most optimal in terms of rapid exothermic microbial activity. There was no strong locational bias (NE, SE, NW, and SW) shown in Layers 1 and 2, all areas of the windrow appeared to heat up evenly. This indicates that good structural and microbial conditions were widespread throughout the windrow. Such conditions would result from high quality, well-balanced feedstocks. Although the trial was established in November, a mild autumn resulted in an extended growing season therefore, more ideal wastes continued to be available later in the season than normal. The lack of elevated windspeeds during the majority of the trial also allowed the rapid and prolonged development of high temperatures within large parts of the windrow. However, results from Layer 3 (Figure 63)

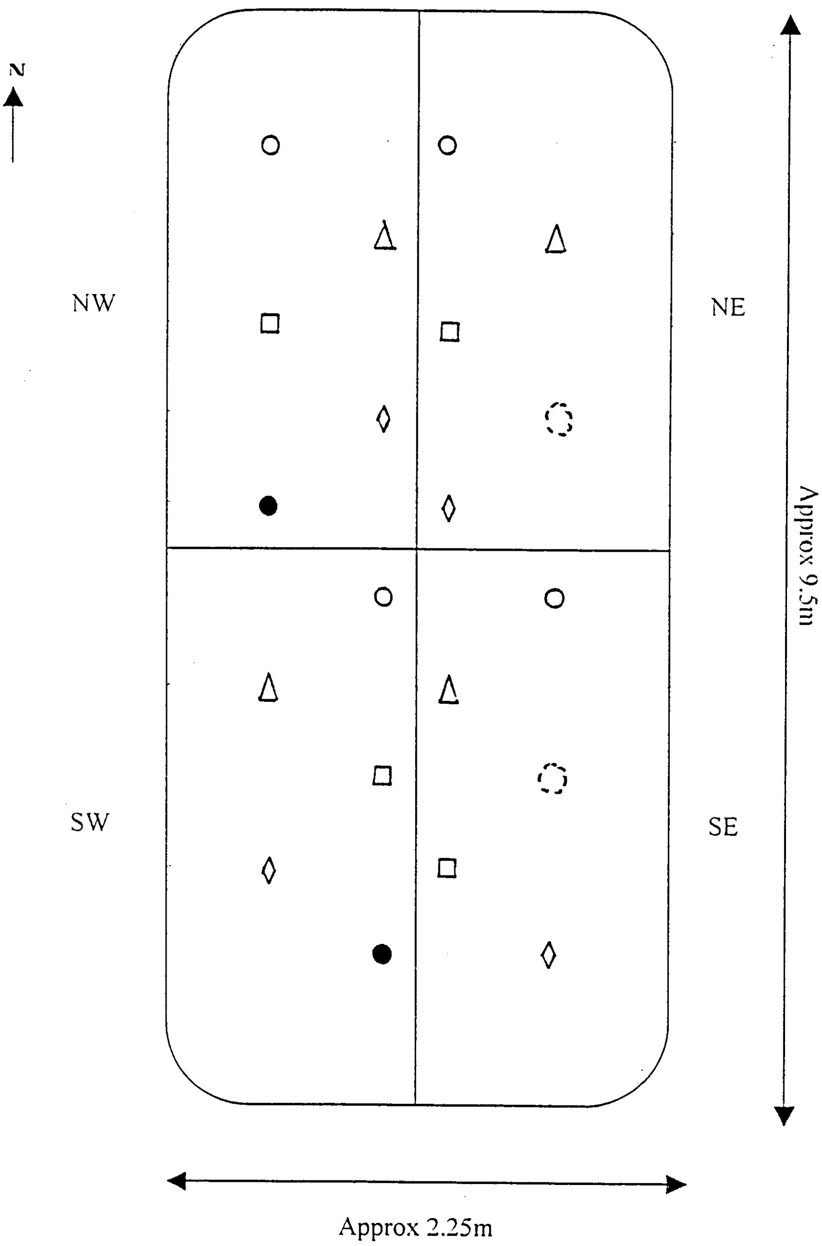
Figure 61: Riverside composting Field Trial 3 (November 2001). Parallel running trial windrow temperatures (°C) Layer 1 (0.5m high) arranged by geographic quarters (NW, NE, SW, SE) over time (h). Temperature trends from operational thermocouples as described in the diagram below are shown in relationship to their location within the windrow structure (approximate dimensions given (m)). The following colours have been used to represent the windrow regions: Blue (NW), Red (NE), Yellow (SW), Green (SE).
NW quarter thermocouples (with depth shown) (○ 1m) (△1m) (□ 1m) (◇ 1m) (● 1m)
NE quarter thermocouples (with depth shown) (○ 1m) (△1m) (□ 1m) (◇ 1m)
SW quarter thermocouples (with depth shown) (○ 1m) (△1m) (□ 1m) (◇ 1m) (● 1m)
SE quarter thermocouples (with depth shown) (○ 1m) (△1m) (□ 1m) (◇ 1m)
◌ Indicates thermocouples yielding partial data sets.

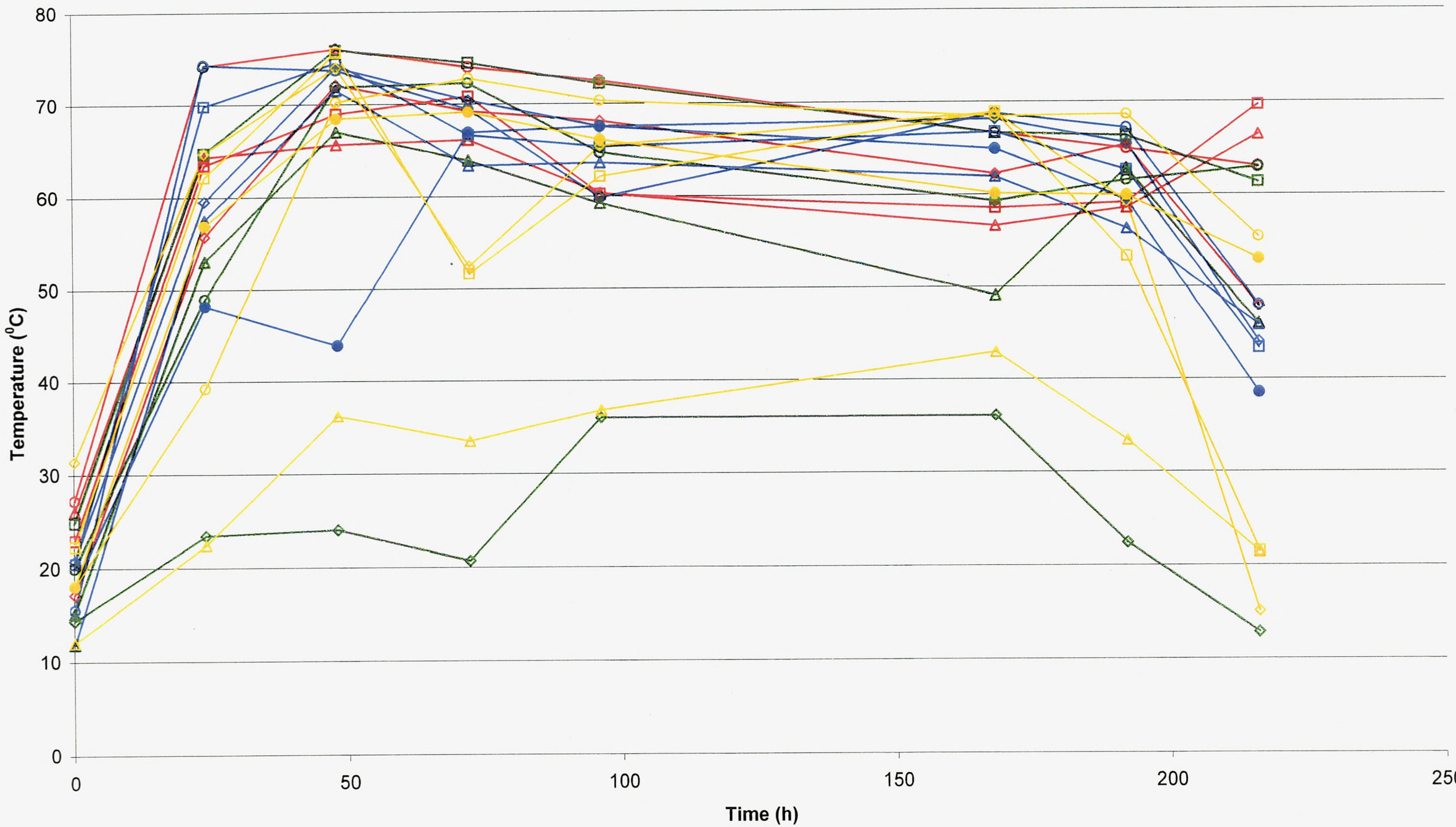




Temperature (^{0}C)
80
70
60
50
40
30
20
10
0
0
50
100
150
200
250
Time (h)

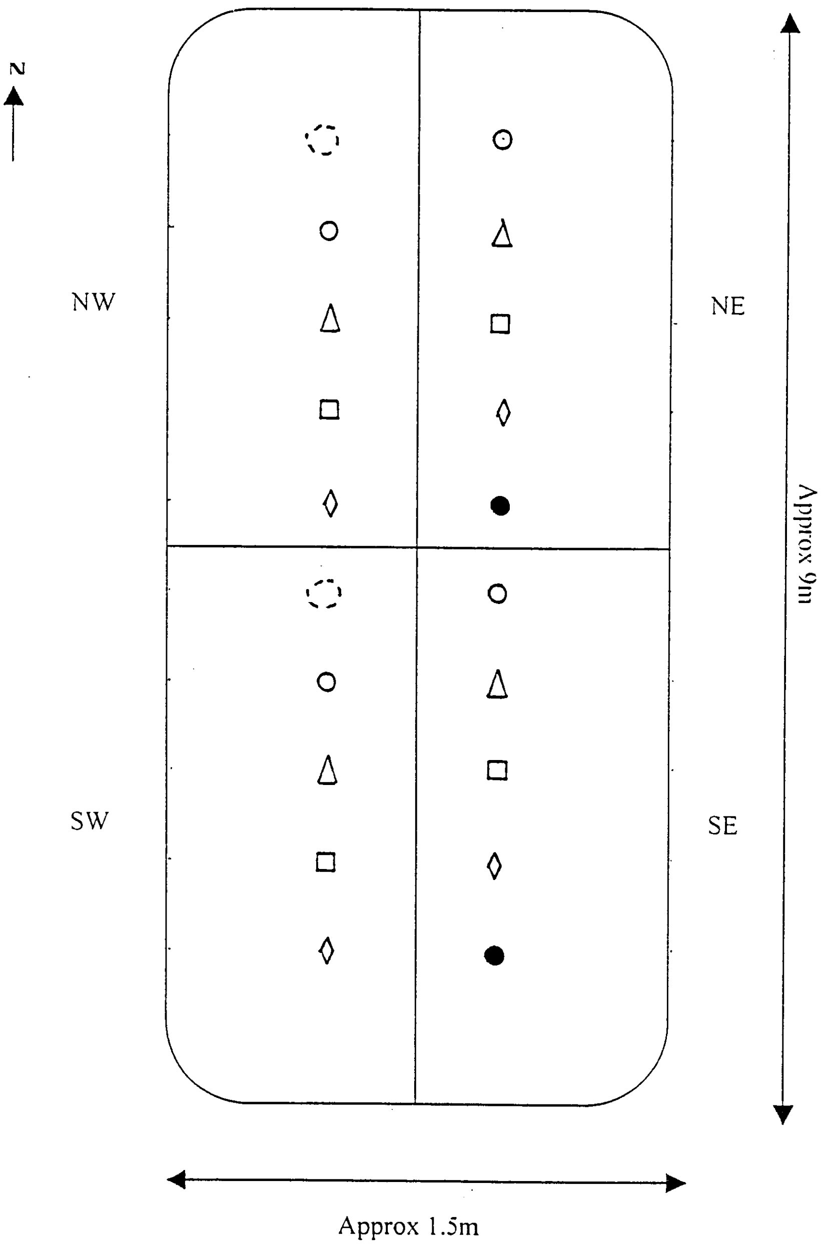
Figure 62: Riverside composting Field Trial 3 (November 2001). Parallel running trial windrow temperatures (°C) Layer 2 (1m high) arranged by geographic quarters (NW, NE, SW, SE) over time (h). Temperature trends from operational thermocouples as described in the diagram below are shown in relationship to their location within the windrow structure (approximate dimensions given (m)). The following colours have been used to represent the windrow regions: Blue (NW), Red (NE), Yellow (SW), Green (SE).
NW quarter thermocouples (with depth shown) (○ 0.5m) (△1m) (□ 0.5m) (◇ 1m) (● 0.5m)
NE quarter thermocouples (with depth shown) (○ 1m) (△ 0.5m) (□ 1m) (◇ 1m)
SW quarter thermocouples (with depth shown) (○ 1m) (△ 0.5m) (□ 1m) (◇ 0.5m) (● 1m)
SE quarter thermocouples (with depth shown) (○ 0.5m) (△1m) (□ 1m) (◇ 0.5m)
⬚ Indicates thermocouples yielding partial data sets.

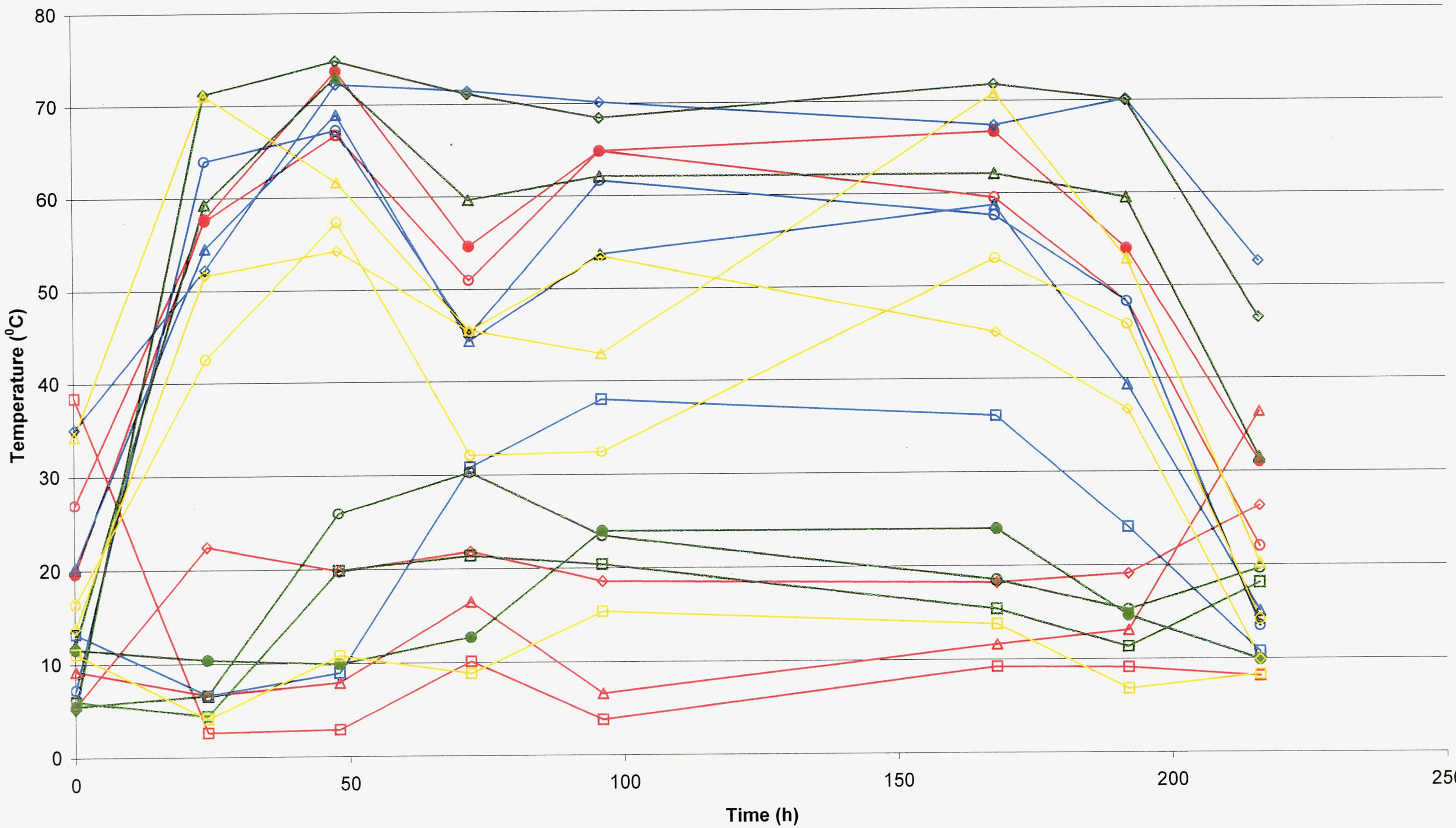




80
70
60
50
40
30
20
10
0
Temperature (°C)
0
50
100
150
200
250
Time (h)

Figure 63: Riverside composting Field Trial 3 (November 2001). Parallel running trial windrow temperatures (°C) Layer 3 (1.5m high) arranged by geographic quarters (NW, NE, SW, SE) over time (h). Temperature trends from operational thermocouples as described in the diagram below are shown in relationship to their location within the windrow structure (approximate dimensions given (m)). The following colours have been used to represent the windrow regions: Blue (NW), Red (NE), Yellow (SW), Green (SE).
NW quarter thermocouples (with depth shown) (**O** 0.5m) (△ 0.5m) (□ 0.5m) (◇ 0.5m)
NE quarter thermocouples (with depth shown) (**O** 0.5m) (△ 0.5m) (□ 0.5m) (◇ 0.5m) (● 0.5m)
SW quarter thermocouples (with depth shown) (**O** 0.5m) (△ 0.5m) (□ 0.5m) (◇ 0.5m)
SE quarter thermocouples (with depth shown) (**O** 0.5m) (△ 0.5m) (□ 0.5m) (◇ 0.5m) (● 0.5m)
Indicates thermocouples yielding partial data sets.



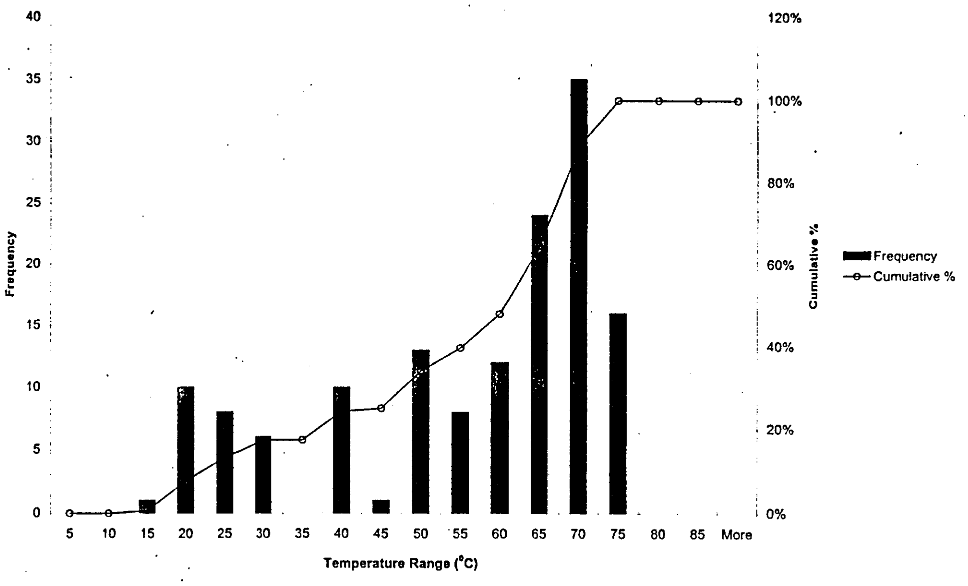


80
70
60
50
40
30
20
10
0
Temperature (^{0}C)
0
50
100
150
200
250
Time (h)

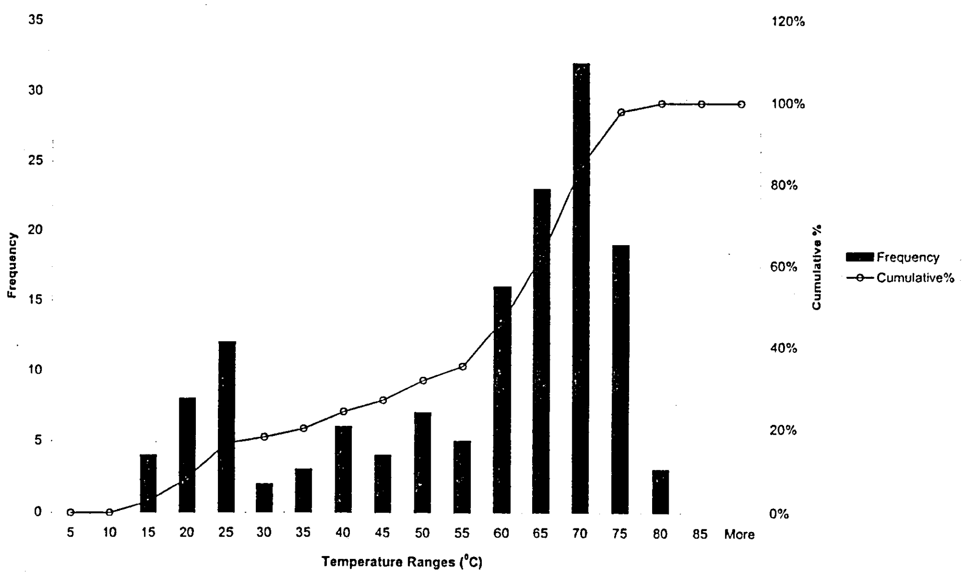
demonstrate that the temperatures in the upper regions of the windrow were more diverse, with many parts of the structure little above ambient temperature. There was no particular locational basis to these temperature trends, however the NW quarter perhaps supported the most thermophilic measurements. There was depression of temperatures in otherwise thermophilic areas between 50 and 100 hours and this corresponded to a period of slightly increased windspeed. The data show that the windrow was essentially split in two, with the first (lower) 1m of the structure exhibiting widespread thermophilic temperatures and the second (upper) metre experiencing a range of temperatures from ambient to thermophilic. Figures 64a-c show the frequency distribution of temperatures within each of the three layers of the field windrow. Data from Layers 1 and 2 reveal a defined skew to the right (the thermophilic zone), with a significant number of readings above 55°C during the period of the trial. However, it should also be noted that there were a significant number of readings in the mesophilic temperature zones. This indicates both the diversity of thermal action and also the fact that cool spots existed within otherwise hot regions (which were not therefore, subject to the pathogen killing power of prolonged elevated temperature) of the windrow. The relative coolness of the upper regions of the field windrow was confirmed by the temperature frequency histogram for Layer 3 (Figure 64c) which displayed a clear skew to the left (the mesophilic zone). Although less hot than the lower layers, Layer 3 still exhibited thermophilic temperatures and this confirms the diverse nature of temperature development and distribution within urban green waste windrows. It is clearly important that physical models of the windrow composting process attempt to simulate such features. The field trial research presented in this study showed that the windrows were not isothermal, and additionally that temperature trends were not equal at a given depth or height or time, but display significant variation. The novel model developed in this study attempted to simulate this phenomenon.

Figure 64: Riverside composting Field Trial 3 (November 2001) (parallel running trial). Temperature distribution histograms. a) Windrow Layer 1 (0.5m high); b) Windrow Layer 2, (1m high); c) Windrow Layer 3, (1.5m high).

a)


Frequency
Cumulative %
Temperature Range (°C)
5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 More
0 5 10 15 20 25 30 35 40
0% 20% 40% 60% 80% 100% 120%
Frequency
Cumulative %

b)


Frequency
Cumulative %
Temperature Ranges (°C)
5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 More
0 5 10 15 20 25 30 35
0% 20% 40% 60% 80% 100% 120%
Frequency
Cumulative%

c)

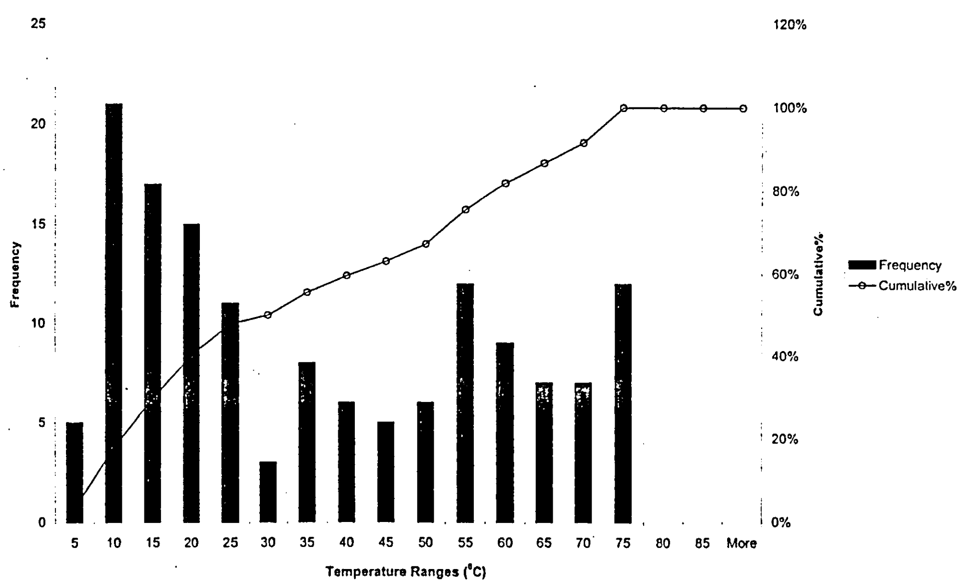

Frequency
Cumulative%
Temperature Ranges (°C)
5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 More
0 5 10 15 20 25
0% 20% 40% 60% 80% 100% 120%
Frequency
Cumulative%

Figure 65 displays the mean cumulative temperature profiles for both the field windrow and the model windrow over the time of the trial. The data show that during the first 48 hours of the parallel experiment, mean cumulative temperature trends within both systems were essentially identical. This is suggestive that temperature build-up within each windrow was comparable. Such findings provide additional evidence that the physical composting model was capable of producing microbially derived thermal behaviour characteristic of that observed in typical field-scale windrows, especially during the initial time period after establishment. After 48 hours cumulative temperature trends between the two windrows began to diverge, but remained similar until around 96 hours. There was a greater difference in cumulative temperatures after this time and this reflected the continued sustained heating observed in the larger volume field windrow. However, it can be noted that the final difference between the cumulative mean temperatures in both windrows was only 61°C. The overlapping of the standard error bars indicate that there was little difference between the field and physical model trial in cumulative temperature terms.

CONCLUSIONS

The running of parallel composting trials using the same feedstocks at the same time within both a field windrow and the physical composting model allowed greater investigation of a number of characteristics of the thermal activity observed within the novel model system. It allowed the direct comparison of temperature development and distribution within the model, with that seen within a field sized windrow when utilizing the same feedstock materials. It is important that, when a novel design of physical model is developed, that not only is it based on general field based observations, but that it is tested directly against the system which it is attempting to simulate. This provides greater

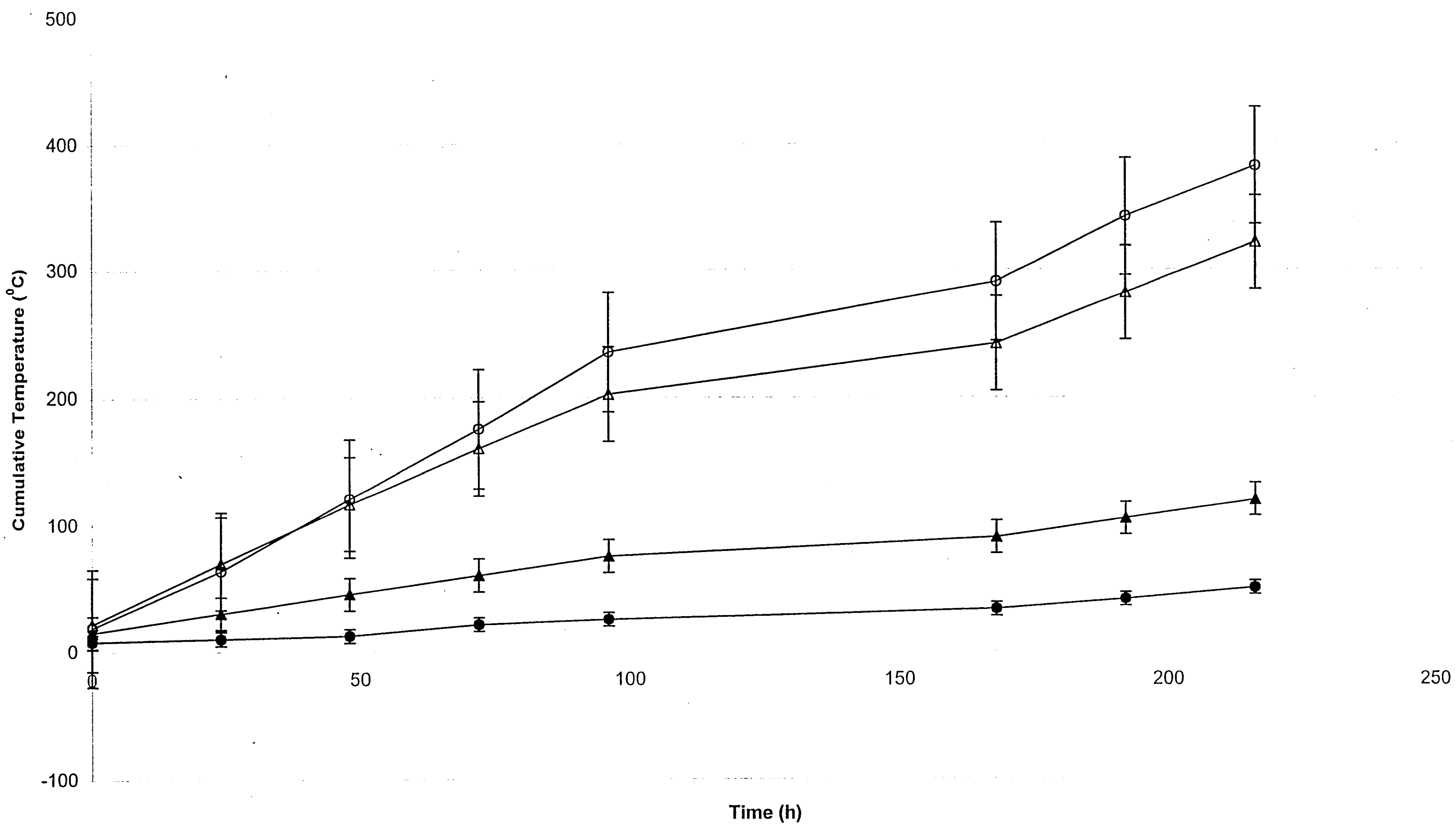
Figure 65: Parallel running trial (November 2001). Cumulative mean temperatures (°C) of field trial windrow and physical compost model windrow against time (h), with respective cumulative air temperatures (°C) shown. Error bars represent the standard error of the data sets.

(○) Cumulative mean field trial windrow temperature

(△) Cumulative mean physical compost model windrow temperature

(●) Cumulative field trial air temperature

(▲) Cumulative physical compost model air temperature



500
400
300
200
100
0
-100
Cumulative Temperature (°C)
0
50
100
150
200
250
Time (h)

confidence that what is being recorded in the model is characteristic of what is occurring in its large-scale counterpart.

The data from the experiments showed that the physical model was capable of modelling the initial 48 hours of urban green waste open windrow composting in some detail. General temperature trends, development and distribution were comparable to that observed in a typical field-scale windrow over this period. The model was able to produce thermophilic temperatures at the rate and distribution similar to those recorded within the field windrow. Temperatures within the composting mass demonstrated a spread that was reflective of that seen in the large-scale example. Heating was not isothermal as variations existed, with the hotter temperatures generally found in the more insulated interior of the structure and cooler temperatures at the surface regions. The trial showed that low-key heating from the inside of the model windrow provided the most realistic method of supportive heating of this system. It allowed the natural development of microbially derived thermophilic temperatures within the feedstocks in a manner that mimicked the distribution of heat typically found in windrows. The model did not employ intense (especially external) heating or heavy insulation as other earlier models have done, because these do not exist in a windrow situation and thus would limit the quality of the model as a representation of open windrow composting. Although the present limited capacity of the model contributes to the reduced sustainability of elevated temperatures and the development of a thermophilic community, the decline of temperatures caused by the pressures of the external environment was in line with field observations. The creation of an external environment simulation system allowed a more realistic model of windrow composting to be operated. Windrows are generally exposed to the effects of the climate. The field trials presented in this study have shown that increased windspeed was an important factor affecting windrow temperature. Therefore, the presence of the above system allowed such features to be considered during the operation of the compost model.

The general behaviour of the model in terms of heating was broadly similar to that observed within the field trial. Although later stage temperature values may be different, the overall pattern of behaviour was essentially the same. This is indicative that what was observed was the same process and that activity was driven by microbial actions within the feedstocks. This trial has shown that the novel physical composting model presented in this study can simulate the thermal behaviour observed in the initial stages of the field-scale open windrow based composting of urban green wastes. Experimentation demonstrated that the novel physical compost model is capable of reflecting the characteristics of open windrow composting, in particular the initial stages of this valuable sustainable waste management process.

CHAPTER 6 – DISCUSSION AND CONCLUSIONS

Open windrow composting of urban green waste and related materials is being widely promoted as a sustainable form of waste management (SEPA, 1999; Department of the Environment, Transport & the Regions, 2000). Although composting has a long history as a waste treatment method (Catton, 1983; Day & Shaw, 2001), it has not been extensively studied in a scientific manner. Therefore, it has relied largely upon empirical methods of process control and "*rule-of-thumb*" in terms of operational management. If composting is to succeed as a modern, efficient, safe and practical means of sustainable waste management then clearly an improved understanding, based on scientific study, of the process dynamics is required.

TEMPERATURE AND OPEN WINDROW COMPOSTING

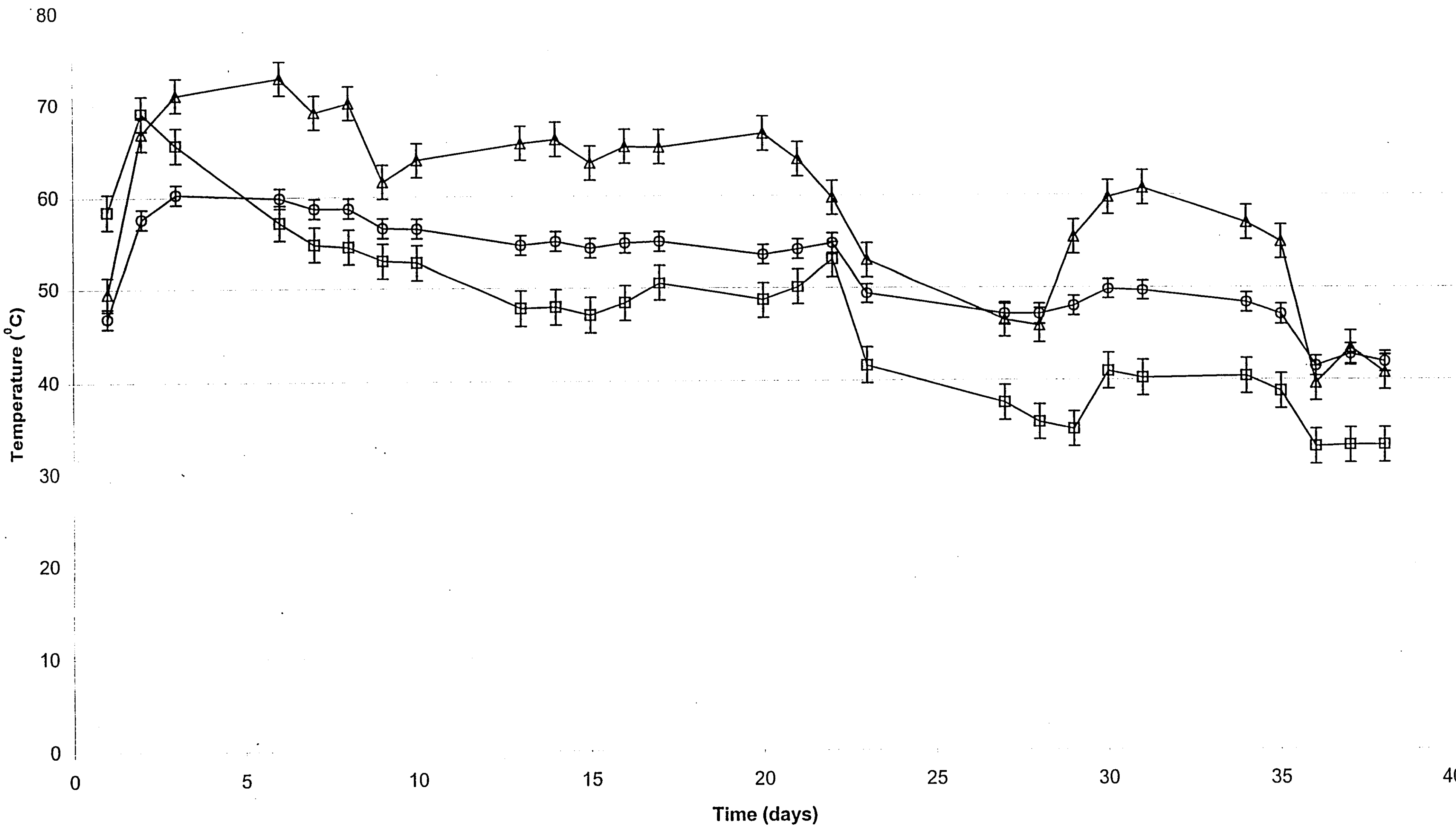
The production of heat (elevated temperatures) *via* exothermic microbial metabolism is a feature of aerobic composting. The association between microbial activity (the "*driving force*" behind composting) and windrow temperature change is known (Rynk & Richard, 2001). Therefore, temperature measurement can be envisaged as an ideal indicator of the composting process. However, there is currently little detailed understanding of the processes of temperature development, change and sustainability within full-scale field or open windrows. It is clearly vital for improved process control, (e.g. optimization of the rate of decomposition, windrow turning cycles and potential pathogen control), that a comprehensive knowledge of windrow thermal behaviour is gained. A major aim of this study was to investigate, using a schematic approach, the temperature profile of urban green waste windrows at an unparalleled level of detail, in order to provide the information that the composting industry requires to introduce improved methods of process control. It is critical that before composting standards are introduced *via* future European Union legislation for example, that these are based on the most comprehensive scientific data available. The current lack of understanding of temperature development and trends has resulted in the use, by commercial composters, of flawed methods of temperature assessment and interpretation. Typical methods employ a limited number of survey points at semi-fixed positions and involve the calculation of mean overall windrow temperature values from these. It is possible to investigate the weakness of such approaches to temperature assessment. The temperature data from Field Trial 2 of this study represent a typical windrow thermal profile. These data were used to derive mean windrow temperature figures using three different methods in order to highlight the problems with current protocols. Firstly, the method employed in this study, which utilized over 100 data points in all regions of the experimental windrow (hereafter, termed the field method). Secondly, a commercial composter's method (hereafter, termed the commercial method) employed 5 equi-distant points each side of the same windrow at a height and depth of 1m. Thirdly, the UK Composting Association's method (Composting Association, 2002) (hereafter, termed the association method) used six data points per windrow (for the purposes of this experiment 3 points each side have been used). Figure 66 shows a comparison between the field method, the commercial method and the association method of determining the mean temperature of the Field Trial 2 (summer) windrow over Days 1 to 38. It is noticeable that the commercial and association methods initially overestimated the temperature. The association method then showed a rapid decrease, whilst the commercial method continued to increase before a slight fall and stabilization, however at a much more elevated temperature than either that of the association or field methods. The results of the association method have given rise to the notion that thermophilic temperatures (greater than 60°C) are detrimental to the process and that for pathogen-kill temperatures (55°C) to be maintained rapid and regular turning need to be employed. The results from the commercial method highlight the problem of using core temperatures at a height of around 1m as the basis of overall windrow temperature assessment. This has been shown, in this study, to result in the overestimation of windrow temperature. The association method suggests a windrow, which was not, in temperature terms, performing

Figure 66: Riverside composting Field Trial 2 (summer). Comparison of mean windrow temperature (°C) assessment methods over Days 1 to 38 of field trial. The Field Method represents the method used in this study (over 100 data points from all regions of the windrow), the Commercial Method represents a typical protocol employed by a UK commercial composter (5 equi-distant points per side at a height and depth of 1m) and the Association Method represents the UK Composting Association's method (3 points each side). Error bars represent the standard error of the data sets.

(○) Field Method mean windrow temperature

(△) Commercial Method mean windrow temperature

(□) Association Method mean windrow temperature



80
70
60
50
40
30
20
10
0
Temperature (^{0}C)
0
5
10
15
20
25
30
35
40
Time (days)

efficiently. Although the field trial experimentation revealed cool spots within the windrow, it was shown that widespread thermophilic conditions existed within the windrow for an extended time (Figures 16 to 22). The twin dangers of using a limited number of data collection points (6 to 10) and having limited spatial variation amongst them is clear. The field method provided an improved estimation of overall windrow temperature over both the association and commercial methods, indicating that moderately thermophilic conditions were exhibited within the windrow. In general terms however, the study showed that the use of simple overall mean windrow temperatures was of limited value and did not give a realistic impression of temperature values and trends within typical field windrows. Temperature development is not isothermal. Spatial and temporal temperature variation is a key feature of windrow based composting (Figures 9 to 13 & 16 to 22). It was demonstrated that all regions of both winter and summer established windrows are capable of producing thermophilic temperatures and should, therefore, be assessed. The sustainability and distribution of these temperature changes reflects both the internal and external pressures placed upon the windrow. This study has shown that the co-existence of cool and hot spots within a windrow at similar depths and heights is a normal feature of such structures. This is important for two reasons; firstly, any temperature measurement regime must be capable of detecting these differences (i.e. sufficient data points must be collected from all regions of a windrow) and secondly, the implications of this phenomenon must be understood (i.e. the requirement for mixing and effects on efficiency of pathogen kill). The temperature data from the field trials in this study showed that the principle reason for turning of windrows is not for aeration, because sustained thermophilic temperatures were displayed even in parts of the windrows subject to slumping and compression (demonstrated through the novel use of electronic tacheometry), suggesting active microbial metabolism, but to mix the contents to ensure maximal exposure to sustained high temperatures (Figures 9 to 13 & 38a & b). A windrow should not be regarded as a single thermal entity, but as a series of interconnected / related units.

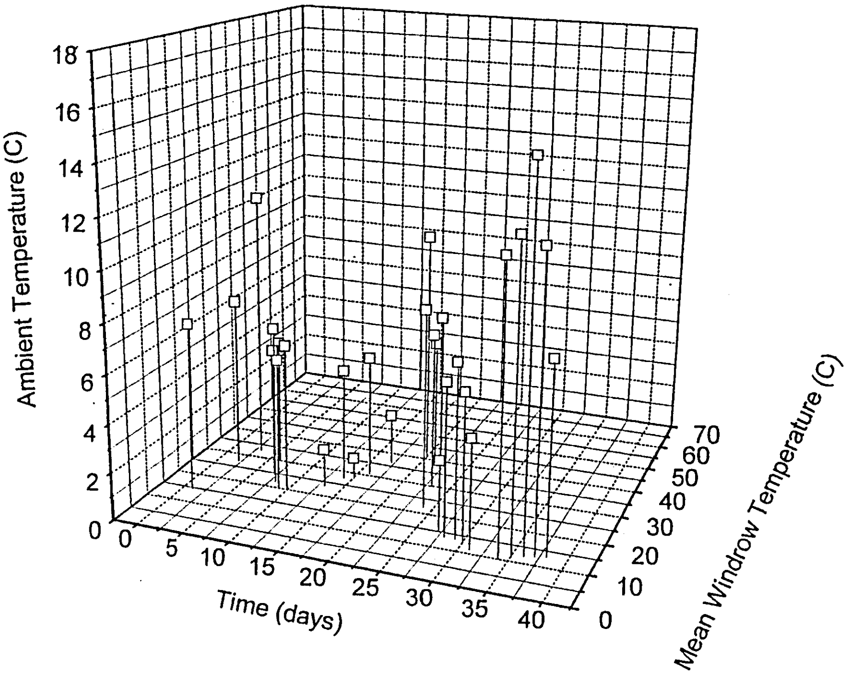
The UK Composting Association (Composting Association 2002) advocates a sanitization temperature requirement of 55°C in the core parts of a windrow for 15 days with at least 5 turnings in that time. This is essentially similar to the US EPA method reported in Table 2. There are flaws in this method. A turning frequency of 3 days is very short. Based on the winter and summer field trial data it was demonstrated that feedstocks took between 1 to 3 days to reach 55°C temperatures and that this only represented a proportion of the total mass of the windrow (at all layers and depths) (Figures 9 to 13 & 16 to 22). This suggests that such a turning frequency would not allow for maintenance of thermophilic temperatures, which is critical for effective pathogen kill (Stenbro-Olsen, 1998). Repeated turning introduces cold air and cool feedstocks into the middle of a windrow, which will induce a lag phase (similar in nature to that seen in the physical model trials, Figures 49 to 51) after reformation, before thermophilic temperatures are regained. A stop-start situation is created, which is clearly not beneficial to efficient composting. Research by Stenbro-Olsen (1998) demonstrated that an exposure time of 48 hours at 55°C did not eliminate pathogens and recommended a regime of 65°C for 72 hours. It is suggested that turning should be less frequent to allow both the propagation of thermophilic temperatures, noting that heat appears to spread out long a windrow (Figures 9 to 13 & 49 to 51), and their maintenance at a sanitizing level. The increasing to 65°C is quite possible in heat production terms by a typical windrow. However, 55°C for an extended time may be easier to achieve (noting the relationship between temperature level / length of exposure time and microbial death; Atlas, 1995).

It is suggested that the number of temperature reading points should be increased to reduce the problems highlighted in the comparative temperature assessment method experiment (Figure 66), and that instead of simply recording an overall mean temperature, that individual temperature trends are plotted and related to windrow position (e.g. height and depth and / or geographic quarter). Additionally, the use of temperature frequency distribution histograms is promoted. Histograms allow the spread of the temperature values (the upper and lower limits), distribution (even or skewed) as well as the frequency of the temperature readings taken during a set period falling within preset temperature intervals to be readily visualized (Figures 28 to 30 & 64). The employment of cumulative temperature plots is also advised, as these have been shown, in this study, to be a valuable tool when accessing the level of and sustainability of heat production within a windrow (Figures 31, 32, 54, 55 & 65). Cumulative temperature plots are less affected by short-term fluctuations in windrow temperature than standard temperature plots, and need a prolonged trend before change is observed (i.e. for positive cumulative temperature change there must be a combination of high temperatures and sustainability, which is equivalent to the requirements for effective potential pathogen reduction).

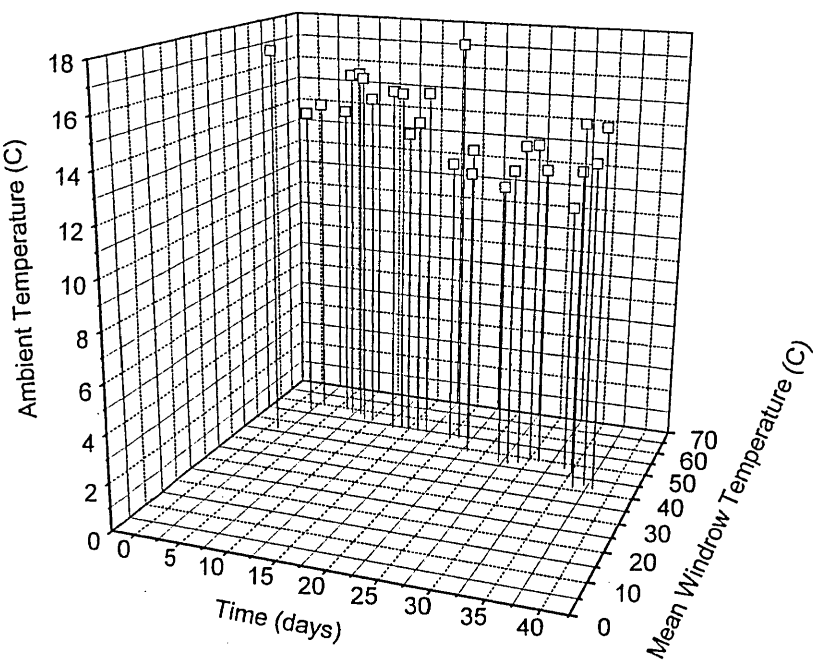
There is a common misconception that ambient temperature can directly affect the production of thermophilic temperatures within a windrow. This study demonstrated that thermophilic conditions could be developed within both summer and winter windrows and the range and distribution of temperature was similar, although sustainability could vary (Figures 25 & 26). This study has shown that there is no connection between ambient temperature and composting activity. Figures 67a & b compare the mean field trial (winter and summer) windrow temperatures against ambient temperature and time. Although there were seasonal ambient temperature differences between the two trials, the figures show that composting activity was not directly linked to ambient temperature. For example, in Field Trial 1 during the main period of temperature increase and hence, microbial activity (approximately Days 13 to 21) the ambient temperature was clearly low. Additionally, some of the highest ambient temperatures during Field Trial 1 were experienced when windrow temperature was low. The data from Field Trial 2 (Figure 67b) reflect in general terms the fact that seasonal temperature trends (warm to cool) and typical composting process temperature trends (hot to cold) coincided. It can be noted that on a short-term basis variations in ambient temperature were not reflected in windrow temperature. This confirms the findings of Stenbro-Olsen *et al*, (1995).

Figure 67: Riverside Composting Field Trial 1 (winter) and 2 (summer). Graphs showing ambient temperature (°C) against mean windrow temperature (°C) and time (Days) (Days 1 to 38). Figure (a), represents winter trial and (b), summer trial.

a)



b)

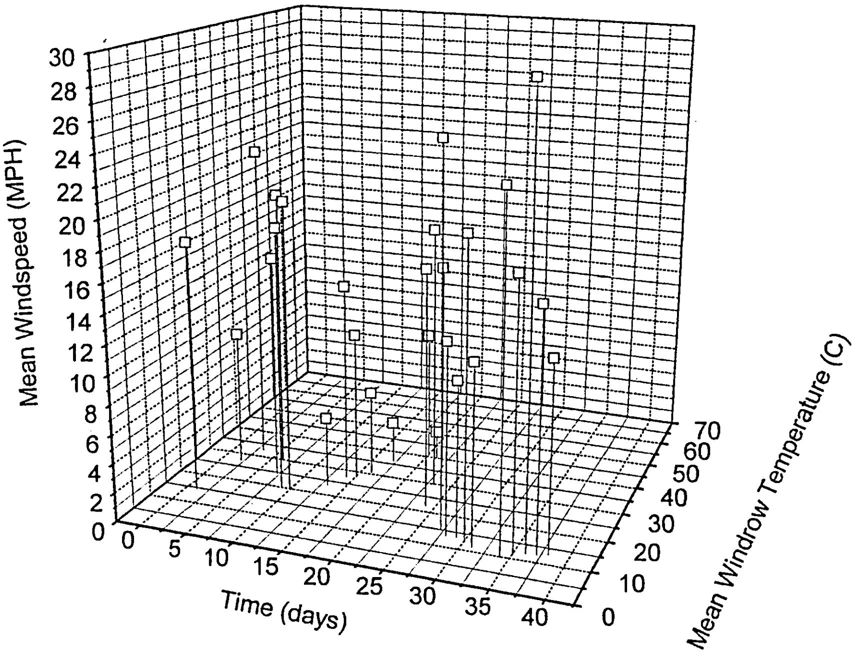


THE INFLUENCE OF WINDSPEED ON WINDROW TEMPERATURE

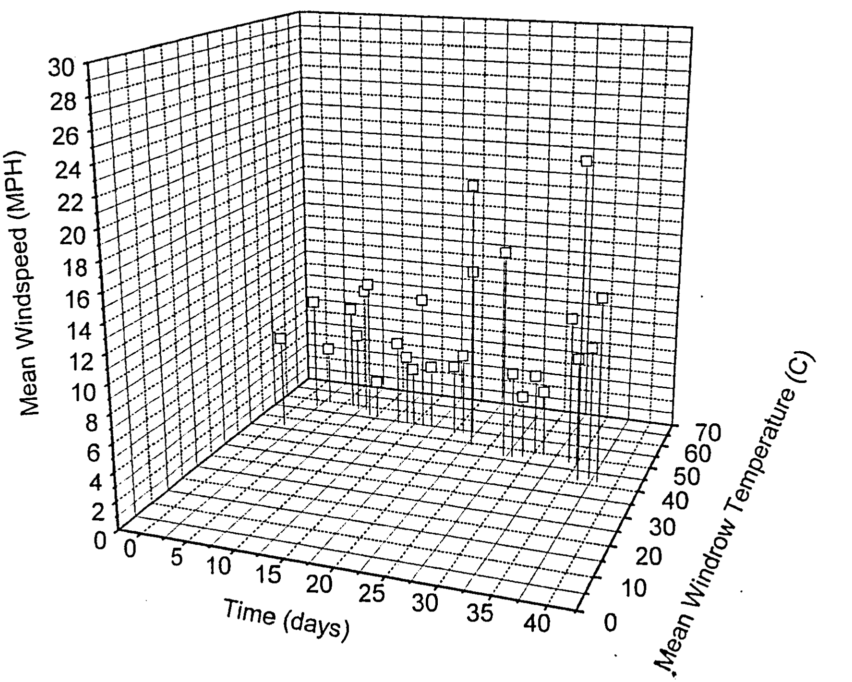
This study demonstrated that the major environmental factor, which influenced the development and sustainability of windrow temperature, was windspeed. Increasing windspeed (greater than approximately 15MPH) significantly reduced windrow temperature (Figures 9 to 14, 16 to 22, 24 & 57). This shows that substantial heat is lost by forced convection. This study revealed that periods of elevated windspeed as short as 24 hours reduced windrow temperature, even in summer established windrows (when the wind chill factor would be less and the overall temperature greater). Figure 68b shows mean windspeed (MPH) and mean windrow temperatures over Days 1 to 38 of Field Trial 2, and shows that after periods of increased windspeed windrow temperatures were depressed. Depths of between 0.5 and 1m (dependant on height) which represented a significant volume of material were shown to be most affected by increased windspeed during the summer field trial (Figures 16 to 22). Prolonged periods of increased windspeed in a similar direction (as experienced during the winter months) was shown in this study to prevent the establishment of thermophilic conditions in the part of the windrow exposed to this force (Figures 9 to 15). It is clear that such a phenomenon has major implications for the management of windrow composting operations concerning the rate of decomposition and the efficiency of potential pathogen reduction. The effects of increasing windspeed are further illustrated in Figure 68a which compares mean windspeed and windrow temperature over Days 1 to 38 of Field Trial 1. There was a noticeable level of elevated windspeed values during this trial, particularly during the initial and final stages (cf. Figure 68b). These corresponded with periods of windrow temperature depression. The mid-period of the trial (approximately Days 13 to 21) shows an interval of low windspeed and increasing windrow temperature (after a period of elevated windspeed and low windrow temperature), which is in direct contrast to the observations of ambient temperature during this time (Figure 67a). The assessment of windspeed and direction at composting sites should be routinely performed. Windspeed measurement should be linked to the

Figure 68: Riverside Composting Field Trial 1 (winter) and 2 (summer). Graphs showing mean windspeed (MPH) against mean windrow temperature (°C) and time (Days) (Days 1 to 38). Figure (a), represents winter trial and (b), summer trial.

a)



b)



temperature assessment and windrow turning regimes as part of an integrated system of process control. The use of windbreaks both natural (e.g. trees) and man-made (e.g. geotextiles) is suggested on particularly exposed sites, as a method of reducing the impact of strong winds on windrow temperature. Trees (e.g. *Salix* and *Populus* spp.) have the additional benefits of acting as effective sound, visual and particulate barriers, as well as natural filters of pollutants (Aronsson & Perttu, 2001).

WINDROW THERMODYNAMICS

Discussions with Dr Steve Reynolds (Reynolds, 2002; Appendix 1) upon the thermodynamics of open window composting systems have allowed data from the winter and summer field trials to form the foundation of a basic model of heat balance in windrows using simple physical arguments (Reynolds, 2002; Appendix 1). An idealized windrow is envisaged with a heat generating core and outer insulating layer. The energy flows within this system and between the environment are described. The rate of heat production in the early stages was calculated as being 2.4W kg^{-1} and the total heat power produced as 72,000W (72kW). The factors of forced (wind) convection, conduction *via* the outer layers and the base, thermal radiation, the latent transformation heat of water as well as biochemical reactions were considered. It is suggested that most of the heat generated by microbial metabolism is lost at the windrow surface by free (natural) and forced convection (wind). This is consistent with the observations presented in this study. The effects of thermal radiation and base-soil conduction on windrow heat balance are minimal. The principle mechanisms for heat transfer within the core region are convection, conduction and the phase transformation of water. Therefore, the importance of good internal structure is highlighted, since the presence of windrow slumping and increased bulk density could account for the variation in temperatures (heat transfer) seen at a given height within the field trial windrows. The movement of oxygen is by internal convection currents. Based on the calculations presented in this model system it is estimated that 0.025 kg s^{-1} of oxygen were required to maintain the microbial heat output of 72kW. This is a considerable level of gas exchange, however, the prolonged existence of thermophilic temperatures in core regions of field trial windrows suggests that the requirements of such microbial metabolism were met.

PHYSICAL-CHEMICAL INDICATORS OF THE COMPOSTING PROCESS

This study indicated that changes in pH, organic matter and bulk density of the feedstocks reflected (in the longer term) the process of decomposition as revealed by windrow temperature trends, but did not have the non-disruptive nature and greater level of sensitivity of well co-ordinated temperature assessments (Figures 35 to 36 & 39 to 40). Moisture content and conductivity assessment were not valid indicators of the state of the composting process, but rather were seen to have a role in the profiling or characterization of feedstocks, final products and potential leachate problems (Figure 43). The production of sugar-acids and the resultant decrease in feedstock pH values is suggested to be a pre-windrow low temperature process that ceases after windrow establishment (Figure 41).

THE PROVING OF A NOVEL PHYSICAL COMPOST MODEL

The need for a convenient and controlled method of studying the composting process has been noted since the 1950s (Wiley, 1956 & 1958). This has lead to the production of a series of physical composting models which have claimed to represent or simulate the composting process (Schulze, 1962; Jeris and Regan, 1973a; Suler and Finstein, 1977; Ashbolt and Line, 1982; Sikora *et al*, 1982; Bach *et al*, 1984; Nakasaki *et al*, 1985; Hogan *et al*, 1989; Adenuga *et al*, 1992; Palmisano *et al,* 1993; Tseng *et al*, 1995; Gilmour *et al,* 1996; Stombaugh & Nokes, 1996; Kaiser, 1996; Papadimitriou & Balis, 1996; Baker *et al*, 1999; Bari *et al*, 2000a & b; Huang *et al*, 2000; Kim *et al*, 2000; Bari & Koenig, 2001). Such physical models have suffered because of the limited amount of information available concerning the thermal behaviour in full sized *in vivo* systems. A major aim of this study was to gain an improved and comprehensive understanding of windrow temperature development and trends (and related physical / chemical behaviour) in typical field scale urban green waste windrows. This was achieved. Secondly, this information was then used to develop a novel physical model. Existing physical model designs have been based on in-vessel style systems. However, this does not represent the system most widely used by commercial composters, open windrows (Rynk & Richard, 2001). It was a specific aim of this project to design and prove a physical model of open windrow composting of urban green waste. Thus, an accurate representation of open windrow composting could be produced. The aim to design and prove such a model was achieved. Through a systematic approach it was demonstrated that microbially derived heat could be produced within the novel model in a manner consistent with that observable within field-scale windrows (Figures 47 to 55). After establishing baseline non-biological heating characteristics, a series of trials, including a parallel model-field trial, were undertaken using green waste feedstocks (Figures 58 to 65). The data from these experiments demonstrated that the model system was capable of simulating the thermal behaviour recorded in field trial windrows during the initial stage of this type of composting process. A non-steady non-isothermal state was created within the model system during the composting of the green waste, which was directly comparable with the conditions observed within the field trials. Comparison with the mean temperature trends of the winter and summer field windrows showed that the model's temperature profile reflected well the seasonality of the waste materials used in the trials in temperature profile typical of feedstocks of that physical-chemical nature (Figure 52). This study produced a viable physical compost model based uniquely (and specifically) on open windrow composting of urban green wastes. The design, operation and validation of the model were based on comprehensive field based studies of large-scale windrows located at a commercial composting site. Windrow temperature trends and behaviour, as well as environmental factors affecting the composting process, were considered during the design and assessment of the system. Low level internal feedstock heating to stimulate natural enhanced microbial activity (cf. windrow starter hot spots) was demonstrated to be a successful, practical and realistic way of counter-acting the problems of poor heat generation within small volumes of waste material. Existing models have sought to externally heat (and maintain) the waste material at thermophilic temperatures (Jeris & Regan, 1973a; Ashbolt & Line, 1982; Bach *et al*, 1984; Palmisano *et al*, 1993; Huang *et al*, 2000). This is counter to what occurs within a windrow, where heat is generated naturally and internally, and there is no isothermal state. Such methods of heating are essentially similar to the placing of waste within an oven (Suler & Finstein, 1977) and view composting simply as a process where chemical changes occur in waste material at elevated temperatures. There is no consideration made for the fact that composting is a natural microbiological process consisting of several different phases being performed at different rates. Recognition of the importance of increased windspeed on windrow temperature development as well as the fact that windrows are typically located out-of-doors, resulted in the creation of a environment simulation system (a combination of the cooling coils, aeration system and the surrounding free air space) within the physical model design. The effect this system had on the development of elevated temperatures within the model was shown to be important and is concordant with the behaviour of large-scale windrows. The interaction between the outer layers of a windrow and the environment, which has been highlighted in these studies, has revealed the flaw of encasing the feedstocks within an insulating jacket in a model situation (Jeris & Regan, 1973a; Whang & Meenaghan, 1980; Sikora *et al*, 1983; Bach *et al*, 1984; Hogan *et al*, 1989; Huang *et al*, 2000). This is common in existing compost models and is an attempt to limit heat loss. However, the simulation of such thermal transfer (windrow to atmosphere), even if negative on the general heating properties of the feedstocks, is vital if a realistic model of windrow composting is to be produced. Any physical compost model must simulate the actual behaviour of the composting system under investigation. If it does not, then the model cannot be creditably used by composters as a system for the improvement of the composting operations or for the accurate predication of the outcome of varying management regimes. The model presented in this study has been demonstrated by experimentation to simulate the behaviour of open windrow composting of urban green wastes.

CONCLUSIONS

This study has revealed that windrow temperature, regardless of seasonal variation in feedstocks, is not isothermal (even within the core regions of the structure), but is subject to constant spatial and temporal variation. The mix of thermal regimes indicates a wide range of microbial niches, and highlights the need to turn windrows to ensure that the maximal volumes of feedstocks have the potential to undergo thermophilic degradation and hence, optimal decay and pathogen kill. Increased windspeed (greater than approximately 15MPH) was demonstrated to be a major factor preventing the development and sustaining of thermophilic temperatures within windrows. The implications of this finding for commercial composters are clear; windspeed and direction measurements should be taken and integrated into site management strategies.

The study has presented a novel physical compost model based upon open windrow composting of urban green wastes (designed with direct reference to the field trial data). The model successfully simulated the initial stages of such a composting system, which was proven by comparison with actual field trial data. The use of low level background internal feedstock heating was demonstrated to be a viable method of stimulating natural microbial activity in small volumes of waste. The introduction of an environmental simulation system and a lack of thermal insulation allowed the *in vivo* interactions between windrow and environment to be simulated within the model system. The study has shown that it is possible to design, build, test and prove a simple low cost physical model of open windrow composting.

SUGGESTIONS FOR FURTHER WORK

Given further funds, time and resources, the following points are envisaged as aims for future research.

- Continued development of the physical model. A larger volume feedstock container to reduce the impact of excess heat loss due to small volume and enhance natural thermogenesis. The incorporation of a more sophisticated environmental simulation system perhaps with a rainfall feature. The development of a continuous temperature data logging system and online analysis of physical-chemical parameters such as pH, moisture and gases within the model is envisaged.
- The use of the physical model to predict the feasibility of composting contaminated feedstocks.
- The further development of a mathematical model to complement the physical compost model.
- A study to further investigate the effect of increased windspeed on windrow temperature development, with the use of various windbreaks.
- The production of a 3D "*fly-though*" computer model based on the temperature trends within a windrow over the composting process, *via* the use of field trial thermocouple based temperature measurements, electronic surveying techniques and suitable computer software.

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APPENDIX 1

S REYNOLDS

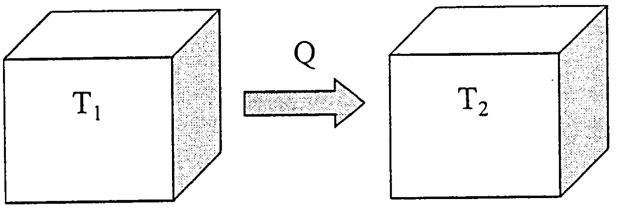
Heat Balance in a Windrow Compost System

1. Basic theory

(a) Thermal capacity

If a quantity of heat Q is supplied to a body of mass m at an initial temperature T_1 its temperature will rise to T_2 such that

$$Q = mc(T_2 - T_1) \text{ Joules}$$



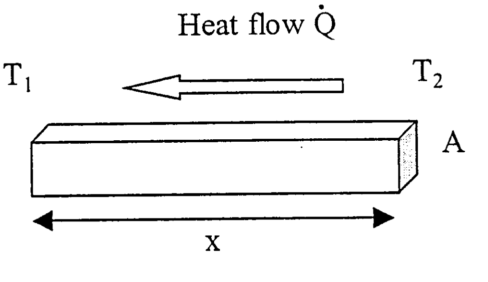
where c is the specific heat capacity of the material. The total heat capacity $C_T = mc$.

(b) Thermal conduction

Thermal conduction is the transfer of heat through a body by means of microscopic processes, including molecular vibrations and electron-lattice interaction. It can occur in all phases of matter but is most significant in metals, certain ceramics and giant covalent molecules such as diamond. Fourier's heat conduction law is

$$\dot{Q} = kA(T_2 - T_1)/x \text{ Watts,}$$

where $\dot{Q}$ is the rate of flow of heat, k is the thermal conductivity of the material, x is the thickness or length of sample, A is the cross-sectional area, and T_1 and T_2 are the temperatures at either end or side of the sample.



Fourier's law may also be expressed as

$$\dot{Q} = (T_2 - T_1)/R_T$$

where $R_T = (T_2 - T_1)/\dot{Q} = x/kA$ is the *thermal resistance*, by analogy with Ohm's Law $R = V/I$. Heat flow is analogous to current, and temperature difference analogous to potential difference or voltage.

(c) Thermal convection

Thermal convection is a term used to describe the transfer of heat to or from a body by a fluid. The fluid may for example gain heat from a hot body and then move away from it by gravitational action (e.g. hot air rises) or be forced away by a current (e.g. by the wind or by a fan). The former is called *natural* convection and the latter *forced* convection.

Heat transfer by convection is written in terms of

$$\dot{Q} = hA(T_2 - T_1)$$

where h is the convection coefficient. Convection is a complex phenomenon. In the case of the windrow, we can make a reasonable analogy with the structure of a building. The following expression for h is given for a Stucco finish wall subject to forced convection such as a wind:

$$h = 12 + 2.6v \text{ W m}^{-2}\text{ K}^{-1}$$

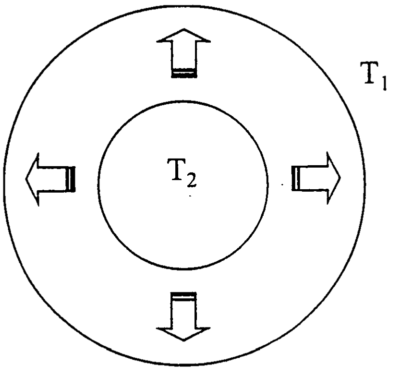
where v is the wind speed in miles per hour.

(d) Thermal radiation

All bodies emit and receive infrared radiation, at typical earthly temperatures the wavelength is approximately 10 micrometres. Stefan's law relates the temperature to the rate of flow of heat due to radiation between two bodies:

$$\dot{Q} = \sigma e A(T_2^4 - T_1^4)$$

where Stefan's constant $\sigma = 5.7 \times 10^{-8}$ and e is the emissivity. e is between 0.2 and 0.3 for vegetation and soils.



(e) The Steady State

This refers to a condition where to all intents and purposes the temperature at every point in the system remains constant over the time scale of interest. In such a case we can apply the idea of continuity – "what goes in must come out" – because none of the heat supplied or generated is invested in an increase in internal energy. This helps to simplify analysis.

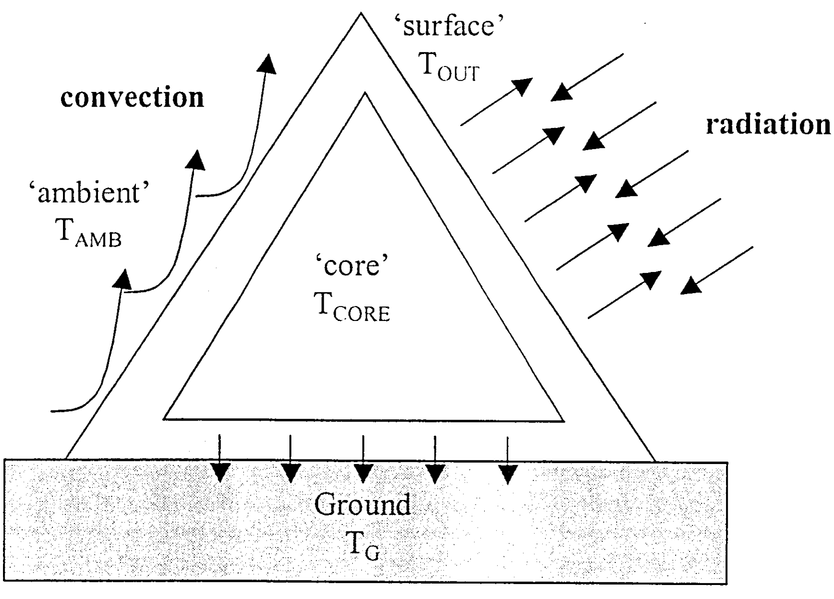
(f) The Transient State

If a system is subject to a step increase (or decrease) in heat flow, it takes some time to respond. The steady state is eventually reached after several *time constants* have elapsed. At times shorter than this, all the heat supplied (or removed) is at the expense of internal energy changes, as no heat has had chance to transfer in or out of the system. This is the opposite situation to the steady state. In broad terms, the better the thermal insulation, and the greater the heat capacity, the longer the time constant will be.

All the above situations can be met and used to advantage in analysing the windrow, when appropriate simplifications and approximations are invoked.

2. The System

You have to start somewhere:



The above represents a physically idealised cross-section through the windrow.

In this model it consists of a heat generating **'core'** whose specific heat capacity is c_{core} and whose thermal conductivity is infinite. It has a temperature T_{core} everywhere and generates $\dot{q}$ Watts kg^{-1}.

The core is enclosed by a **'jacket'** of composting material, of zero specific heat capacity, effective thermal conductivity k_j, porosity p and thickness t_j. The term 'thermal conductivity' is used loosely here, to include the flow of heat both by conduction and by *mass transport* - the warm gases and vapours produced by metabolic processes going on in the core will also percolate through it.

Heat passes from the core, through the jacket and is lost by a combination of free + forced convection and radiation at the surface. The convection coefficient is h_c.

The assumed dimensions in the following calculations are: height 3 metres, base width 4 metres, length 10 metres. This gives a volume $V = 60$ m^3, a surface area in contact with the open air $A_A = 84$ m^2 and a base area $A_B = 40$ m^2. The exact dimensions of the windrow don't matter greatly in terms of obtaining a general model.

In developing the model, it is assumed that the core is essentially water, with c = 4200 J kg^{-1} K^{-1}, and has a porosity $p = 0.5$, giving an effective density ρ = 500 kg m^{-3}. The thermal conductivity and thickness of the jacket cannot easily be estimated, but it will be shown below that a certain plausible range of values fit the observations.

3. Preliminary considerations

It is argued that the above model contains all the essential thermal ingredients to allow a crude model of the heat balance to be constructed, from which a more refined model could be developed. We stress this is only a thermal model and takes no account of specific metabolic processes and requirements such as oxygen and nutrient supply. However, a finite element numerical model containing dependent heat sources and realistic boundaries could in principle be developed.

It is observed that the windrow temperature is influenced by strong winds. A wind rising from an average value of 5-10 mph to 20+ mph can lower the core temperature by several degrees. This tells us firstly that significant heat is lost by forced convection, and secondly, since the lag between high winds and the observed temperature fall is of the order of one day, the thermal time-constant τ is about one day. This allows two pieces of physics to be pinned down:

(a) The rate of heat production

In the first day, core temperature rises of up to $\dot{T}_{core} = 2$ K hr^{-1} (5.6x10^{-4} K s^{-1}) have been recorded. Observations based on the effect of a strong wind on the temperature profile suggest the windrow thermal 'reaction time' τ is of the order of a day or so. As the maximum temperature is achieved on a timescale on the order of τ, we can reasonably assume that most of the heat produced in the first day or so has not had chance to leave the core. Therefore the rate of heat production (at least in the early stages) is simply

$$\dot{q} = \dot{T}_{core} c_{core} = \mathbf{2.4\ Watts\ kg^{-1}}$$

As the core volume is approximately the total volume, the total heat power produced is

$$\dot{Q}_{TOT} = m\dot{q} = \rho V\dot{q} = 500 \times 60 \times 2.4 = \mathbf{72{,}000\ Watts}$$

(b) The temperature difference $T_{core} - T_{amb}$

It can be shown from transient heat theory that the thermal time constant of the system must equal

$$\tau = R_T C_T .$$

Now, from the above, it is suggested that $\tau = 1$ day (86,400 seconds), and also that $R_T = (T_2 - T_1)/\dot{Q} = (T_{CORE} - T_{AMB})/72{,}000$, $C_T = mc = 30{,}000 \times 4200 = 1.3 \times 10^8$ J K^{-1}. This yields

$$T_{CORE} - T_{AMB} = (72{,}000 \times 86{,}400)/(1.3 \times 10^8) = \mathbf{48\ deg\ C}$$

4. Forced Convection

The forced convection loss must support the outward heat flow of 72kW from the core. We therefore require the 'wind' to abstract this. From the convection equation

$$72{,}000 = hA(T_{OUT} - T_{AMB}), \text{ giving}$$

$$T_{OUT} - T_{AMB} = 72{,}000/(50 \times 84) = \mathbf{17\ deg\ C}$$

If we choose T_{AMB} = **10 deg C**, then T_{OUT} = **27 deg C** and T_{CORE} = **58 deg C**. These figures are not in conflict with observation.

5. Conduction across jacket

Measurements have shown that high temperatures are reached just a few centimetres into the windrow, so the jacket thickness cannot exceed this without becoming unrealistic. If we therefore assume $t_j = 0.025$ m, then from Fourier's law

$$72{,}000 = k_jA(T_{CORE} - T_{OUT})/t_j, \text{ giving}$$

$$k_j = (72{,}000 \times 0.025)/(84 \times 31) = \mathbf{0.7\ W\ m^{-1}\ K^{-1}}$$

Such a figure is not unreasonable – it is a factor of two smaller than for soils, and similar to liquid water.

6. Thermal radiation

According to the above model, where we have ignored thermal radiation, in the steady state the peak rate of energy transfer out of the windrow surface is about **850 W m^{-2}**. This figure allows us to assess whether radiation will have much effect on the energy balance of the windrow.

(a) Heat loss through radiation into 'space'

Let us assume a mean windrow surface temperature of 300 K and emissivity of 0.25, radiating into a universe at absolute zero. From Stefan's law we have

$$\dot{Q}/A = \sigma e(T_2^4 - T_1^4) = 5.7\text{x}10^{-8} \times 0.25 \times 300^4 = \mathbf{115\ Watts\ m^{-2}}$$

This represents an extreme value because it is often cloudy, and also the terrestrial surroundings will be only 20 degrees or so cooler than the windrow surface. If we assume the windrow is largely enclosed by its surroundings, at say 280 K, then this figure decreases to a mere **28 Watts m^{-2}**.

(b) Heat gain from the sun

The sun provides about 1400 Watts m^{-2} of radiation at the top of the atmosphere. Air, moisture, clouds etc. absorb and scatter a variable amount. There are also the diurnal and seasonal variations of the sun in the sky relative to the location of interest (day/night, summer/winter). The daily average insolation values in the UK at ground level vary between 40 and 210 Watts m^{-2}. Including the windrow emissivity factor of 0.25 these figures become **10 and 50 Watts m^{-2}** respectively. See **http://www.becosolar.com/general.htm**

In conclusion it seems highly likely that radiative loss and solar radiation gain do not significantly influence the heat balance during windrow composting (at least not directly). The 'weather' may however be important as wind speed, direction, humidity and air temperature will all influence the convective properties of the atmosphere.

7. Heat loss by conduction through the base

This source of heat loss is rather uncertain. If we assume the soil temperature to be uniform and to remain constant at T_{AMB} (i.e. the earth acts as a perfect heat sink) then the rate of heat loss from the core by conduction through a jacket layer into the ground is

$$\dot{Q} / A = k(T_{CORE} - T_{AMB}) / t$$

We then have to decide on a value for k. Soil has a value of typically 1 W m^{-1} K^{-1}, green waste and compost will be somewhat less than this. If the jacket layer is again considered to be about 0.25 m thick, we obtain a rate of heat loss of 192 W m^{-2}. Over the entire base area of 40 m^2 this becomes 7680 W in total. Recalling that 72,000 Watts is produced by the core, the fraction lost through the base is some **11%** of the total. Thus the composting processes in the core of a windrow are probably largely unaffected by heat loss through the base.

8. Latent heat transformation of water to water vapour

The phase transformation of liquid water to water vapour is a very effective means of heat dissipation, as the latent heat capacity of water is large, 2.5×10^6 J kg^{-1}. There are several ways of assessing the extent to which 'transpiration' is important as a heat loss mechanism. Note that this is not 'over and above' what has been considered earlier; we are just trying to account at a mechanistic level for the magnitudes involved.

(a) Rainfall

The average daily rainfall in eastern Scotland is approximately 2 mm/day. If this falls on the base area of 40 m^2 it would amount to some 80 kg/day. If it were all converted to vapour in the windrow this would require 200×10^6 Joules/day or a rate of supply of 2.3 kW, just 3% of the total power generated of 72 kW.

(b) Loss of moisture from green waste

Figures (RJI) suggest that moisture content can vary between 30% and 45%. This may indicate the inhomogeneous nature of the waste, and thus a sampling variability, rather than any time evolution of the moisture content. For example, in trial 2 between weeks 2 and 4 there is a 15% *increase*, some 4500 kg, or 4.5 m^3 of water. This would require 11 cm of rain over a fortnight, about 20% of the annual average, to be retained. Did this happen?

There is an apparent *decrease* in moisture content of some 8% over the first week, but the changes per week over the remainder of the period (notwithstanding the apparent downpour) are of order 2%. Vapourising 8%/week (340 kg/day) of water would correspond to an average latent heat loss of 9.8 kW, or 14% of the total heat generated by the core. Thus such phenomena may be significant.

9. Chemical considerations

If the reaction

$$C_6H_{12}O_6 + 6O_2 \Rightarrow 6CO_2 + 6H_2O + 2830 \text{ kJ/mole}$$

supplies the heat in the windrow system, the 72 kW produced is equivalent to combustion of 72/2830 = 0.025 moles/second of glucose. This would also produce 0.15 moles/second of carbon dioxide (to be removed) and water, and require 0.15 moles/second of oxygen (to be supplied).

If the windrow was 50% porous, it would at 'time zero' contain about 60/2 = 30 m^3 of air = 6 m^3 of oxygen (about 6 kg). 1 mole of oxygen is 32×10^{-3} kg, thus 6 kg corresponds to about 180 moles of trapped oxygen. This would be used up after about 180/0.15 seconds, or 20 minutes. Thus to maintain steady respiration, air needs to be replenished on this timescale, by convection currents (air drawn in at the base being heated, and then displaced upwards by buoyancy forces), or by diffusion (this seems far too slow) or by wind (unlikely as a primary mechanism since composting doesn't stop on a still day!). This is a big turn-over of gas, 30 m^3/20 minutes = 0.025 $m^3\ s^{-1}$ = 0.025 kg s^{-1}. If the temperature increase is 48 deg C, and the specific heat capacity of air is about 1000 J $kg^{-1}\ K^{-1}$, a heat loss of 1200 Watts is predicted, only 2% of the total heat generated.

Water is also produced by respiration, at a rate of about 240 kg/day. This is only about 0.8% of the total moisture content, of a similar order to rainfall, and will assist in replenishing water lost as vapour.

10. Conclusions

- In broad terms, the general principles governing the energy flows in a windrow can be understood using simple physical arguments.

- Heat generated by microbial activity is dissipated at the windrow surface primarily by a combination of free and forced convection. Radiation gains and losses appear to be negligible, as does conduction into the ground.

- It is proposed that a thin 'jacket' of material a few cm thick surrounds the active core. This layer will not achieve high enough temperatures for composting, it will also be quite dry and thus behave as a good thermal insulator.

- Heat transfer within the core occurs by a combination of conduction, convection, and phase transformation of water (latent heat). The internal convection currents replenish the oxygen required for aerobic respiration and remove the carbon dioxide produced.

- Over the life cycle of the windrow, relatively little material is 'lost', and the apparent volume reduction is due to a reduction in porosity as structural matter is broken down.